# Assessment of water quality impacts for different management practices using SWAT model

by

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*"Praise be to Allah, the Cherisher and Sustainer of the worlds"*

*A Ph.D. degree represents the highest educational accomplishment in my career, a childhood dream that comes true.*

*There are no better individuals to dedicate this achievement than to*

*my father, Jamil for instilling in me a sense of value in the pursuit of knowledge;*
*my mother, Asmat for her constant prayer;*
*my brothers and sisters for their support and prayers;*
*my wife Muddser, for her support and love; and*
*my two children Sarmad and Omar, whom I hope will develop the passion to learn and desire to explore the frontier of knowledge for the betterment of the human being.*

*I dedicate this work..............*

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## ABSTRACT

The high yield input strategy has been successful in narrowing the gap between food and fiber requirements and the growing population. However, at the same time it has also threatened the sustainability of land and water resources. Best management practices (BMPs) are technically feasible methods for preventing or reducing nonpoint source pollution to a level compatible with water quality goals. Long-term monitoring of BMP impacts is essential to assess their effectiveness under different conditions. However, it is impractical to monitor all BMPs under all conditions due to time and cost constraints. Computer simulation models provide an alternative to evaluate the response of soil and crops to a range of management practices in an efficient and cost effective way. Testing and evaluation of computer models require the use of extensive field data to ensure that they are reliable for the prediction of management effects. This study was designed to: (1) Calibrate and evaluate the subsurface drainage component of SWAT model; (2) Test the ability of SWAT (version 99.2) model for predicting nitrate-nitrogen ($NO_3$-N) losses with tile flow, by comparing the model output versus measured data; (3) Application of SWAT model on watershed scale.

In general, SWAT adequately tracked the measured tile drain flows, except that the cumulative monthly tile flows were consistently under-predicted. Differences of -8.4 to 6 and 2 to 11% were determined for the annual simulated tile flows as compared to the corresponding measured flows for the calibration and validation period respectively.

Calibration of SWAT was performed using tile flow $NO_3$-N loss data measured in 1995 while validation was conducted by comparing the model output

with measured $NO_3$-N losses with tile flow observed in 1993-94 and 1996-97. Differences ranging from 2 to 10% and -7.34 to 5.50 were found between annual $NO_3$-N losses during the calibration period and validation period respectively, indicating that the model tracked the monthly observations reasonably well. However, the peak $NO_3$-N losses were consistently under-predicted for all three combinations of tillage and cropping systems.

The SWAT model was used to estimate the flow and nitrate loading for UMRW watershed. The model was calibrated for stream flow and $NO_3$-N data measured in 1999 at the outlet of the watershed and model was validated for 2000 and 2001 period. The model accurately tracked most of the peak flow events that occurred during the year, although the peaks were usually over predicted. The model tracked the flow reasonably well but model was unable to track the nitrate trend. The underprediction between the simulated and measured annual flow for year 1999 was 24%, while 35% for year 2000 and 12% for year 2001. The $NO_3$-N was over predicted by 25%, 22% and 108% for 1999, 2000, and 2001, indicating the poor performance of SWAT model in $NO_3$-N simulation.

# CHAPTER 1. GENERAL INTRODUCTION

## Introduction

Agricultural products fulfill most food and fiber requirements of human beings. With the passage of time, the increase in population and improved living standards have found the agriculture sector to increase its production by using various improved agricultural inputs and practices. Use of chemical inputs such as insecticides, herbicides, and inorganic fertilizer have become integral part of intensification of agricultural production systems in spite of their negative effects on the environment. This high yield input strategy has been successful in narrowing the gap between food and fiber requirements and the growing population. However, at the same time it has also threatened the sustainability of land and water resources.

The excessive use of agricultural chemicals has been identified as a major contributor to soil and water pollution (Keeney, 2002). Several studies have reported increased nitrate-nitrogen concentration in tile drainage water and in deeper ground water resources, as a result of poor management and higher application rates of nitrogen (N) fertilizer (Baker and Johnson, 1981; Kanwar and Baker, 1991). Excess nitrogen in the estuaries of the oceans enhances growth of aquatic organisms to the point that they affect water quality and lower dissolved oxygen levels (Downing, 1999; Rabalais et al., 2001). Nitrogen is commonly a key causal factor for hypoxia in salt water. The total amount of nitrogen load from the Mississippi River to the Gulf of Mexico has increased over the last 30 years; in particular, the nitrate load is three times greater than 30 years ago (Goolsby et al., 2001).

As pointed out by Hallberg et al. (1986), subsurface drainage studies can be a useful tool for assessing the impact of agricultural management practices on the groundwater and surface water quality. Monitoring of subsurface drain flows to investigate tillage effect should provide more conclusive results because field drainage systems incorporate the complexity of the real soil-water-crop system. Tile drained areas are also readily available for water quality research at many research stations as well as production fields, providing a methodology to study field-scale transport of solutes at relatively modest cost.

Best management practices (BMPs) are technically feasible methods for preventing or reducing nonpoint source pollution to a level compatible with water quality goals (Novotny and Olem, 1994). The evaluation and assessment of BMP impact can be accomplished in two ways: (1) by collecting field data over an extended time period, or (2) by using computer simulation models developed from current scientific knowledge. Long-term monitoring of BMP impacts is essential to assess their effectiveness under different conditions. However, it is impractical to monitor all BMPs under all conditions due to time and cost constraints. Computer simulation models provide an alternative to evaluate the response of soil and crops to a range of management practices in an efficient and cost effective way (Bakhsh et al., 1999; Zacharias and Heatwole, 1994). Nevertheless, testing and evaluation of computer models require the use of extensive field data to ensure that they are reliable for the prediction of management effects.

Numerous models have been developed that vary in complexity for simulating flow, and in some cases agricultural chemical movement, through soil. The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Srinivasan et al., 1998) is a relatively new model and is developed to predict the effects of different management scenarios on water quality, pollutant loadings and sediment yields by accounting for variation in soil, climate, and land use across a watershed or river basin. The specific objectives of this study were to:

1. Evaluation of tile flow component of SWAT model under different management systems.
2. Calibrate and validate the SWAT model for predicting nitrate-nitrogen losses with tile flows under different combination of tillage and cropping system.
3. Calibration and validation of the SWAT model for the Upper Maquoketa River watershed (UMRW).

**Dissertation Organization**

This dissertation is organized into six different chapters. The first chapter includes an introduction to the topic of the research, and explains the organization of the thesis. More detailed literature review was made in chapter 2, on the subject that will be discussed in the following chapters. The third chapter describes the application of SWAT model to simulate the tile flow under different management systems. The fourth chapter explains the calibration and evaluation of SWAT model to investigate the impact of different management systems on nitrate-nitrogen losses with the drainage water under continuous corn, corn-soybean and soybean-corn rotation under different tillage systems. The fifth chapter describes the calibration and validation of SWAT model on the Upper Maquoketa river watershed. Finally, the sixth and the last chapter summarize the overall conclusions of the study and suggest related topics for future research work. Because of the publication guidelines, tables and figures have been placed at the end of each chapter.

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# CHAPTER 2. LITERATURE REVIEW

## Subsurface Drainage and Nitrate Transport

Agricultural drainage is defined as a timely removal and disposal of excess water from agricultural land by means of open and/or subsurface drainage methods. Subsurface drainage of wet areas alters the time and route by which excess precipitation reaches surface water. Decrease in the amount of overland flow, increases in percolation, lower water table, and alteration in the flow path of some of the infiltrated water result from subsurface drainage (Baker and Johnson, 1976).

Artificial subsurface drainage is required to maintain the productivity of poorly drained soils and is practiced on over 30% of the soils in the Midwestern USA (Hatfield, 1998). Agrochemicals and other fertilizer sources are extensively used in the region to increase crop production, but are also significant nonpoint sources of groundwater and surface water pollution. Subsurface tile drains are key pollution pathways to surface water, especially for nitrate-nitrogen ($NO_3$-N), as reported by Kanwar et al. (1999), Jaynes et al. (1999) and Cambardella et al. (1999). Over application of nitrogen from fertilizer or manure to continuous corn has been associated with excess residual soil $NO_3$-N at the end of the growing season which may be more susceptible to leaching over winter when precipitation exceeds evapotranspiration (Katupitiya et al. 1997). The lower nitrogen requirement of corn following soybeans also creates the potential for $NO_3$-N leaching (Lory et al., 1995). David et al. (1997) determined, in their six-year study period, that an average of 49% of the pool of residual $NO_3$-N remaining after harvest was leached through drain tiles and exported to the river. Also Bakhsh et al. (2002) reported a significant linear relationship between growing season precipitation and subsurface drainage volume and also a significant relationship between subsurface drainage volume and $NO_3$-N leaching losses with subsurface drainage water.

The subsurface flow response of a given soil system can be influenced by soil type, agricultural management practices, rainfall pattern, and topography. Tillage practices directly affect the soil water properties of the surface soil and soil leaching characteristics (Kanwar et al., 1988). Tillage practices can also influence the distribution and continuity of macropores that can act as preferential pathways for rapid movement of water and chemicals to the groundwater (Singh et al., 1991). Numerous field studies have been conducted to assess the impacts of different management and cropping systems on $NO_3$-N losses to tile drains (e.g., Kanwar and Baker, 1991; Kanwar et al., 1997; Kanwar et al., 1998; Kanwar et al., 1999; Randall et al., 1997; Randall 1998). These experiments have provided critical insights into the processes that dominant $NO_3$-N losses to tile drains, and have provided important guidance on solutions to the problem.

Goolsby et al. (2001) reported that higher stream flow could influence $NO_3$-N in two ways. First, the volume of flow can be larger and more $NO_3$-N will be transported unless concentrations decrease. Second, the higher precipitation would leach more accumulated $NO_3$-N from soils and would actually cause $NO_3$-N concentrations to increase. Similar scientific evidence has been suggested that nitrogen levels could build up in soils during dry years from mineralization processes and reduced uptake by crops, and more nitrogen was flushed out in the succeeding wet years (Randall, 1998). These studies suggest the critical role of subsurface drainage flow rates in transporting $NO_3$-N from agricultural lands to the Mississippi river and ultimately to the Gulf of Mexico. Randall and Mulla (2001) concluded that least economical way to reduce $NO_3$-N loadings to surface water would be to abandon the subsurface drainage systems or find alternate ways to minimize its adverse effects. These studies, however, emphasized the need to study the subsurface drainage trends on long-term basis over space and time domains to better analyze the subsurface drainage effects on the ecological environment and to promote the use of sustainable farming practices (Kanwar et al., 1997; Bakhsh et al., 2000).

**Nitrate and Hypoxia**

Excess nitrogen in the rivers, lakes and groundwater can be toxic to humans, and causes water quality problems in natural water systems (Hallberg and Keeney, 1993). Excess nitrogen in the estuaries of the oceans enhances growth of aquatic organisms to the point that they affect water quality and lower dissolved oxygen levels (Downing et al.,1999; Rabalais et al., 2001).

The Gulf of Mexico, like many other estuaries and coastal areas in the world, has seen major ecosystem changes because of low oxygen levels caused by excessive input of sediments and nutrients arising from industrial and agricultural activities in the Mississippi River Watershed. Higher productivity of phytoplankton because of increased nutrient input has provided more organic residue from dead cells. This has led to increased oxygen consumption during decomposition of the material. The result has been the development of an extensive region of oxygen deficiency consisting of less than 2 mg/L of dissolved oxygen, commonly referred to as hypoxia (Rabalais et al., 2001). The area of hypoxia zone in the Gulf of Mexico fluctuates widely, but is generally on the increase over time (Rabalais et al., 2002).

Nitrogen is commonly a key causal factor for hypoxia in salt water, while phosphorus tends to be a limiting nutrient in fresh water systems. Nonpoint sources are thought to contribute as much as 90 percent of the nitrogen flowing into the Gulf of Mexico annually. In an average year the Mississippi River discharges 1.57 million metric tons of nitrogen into the Gulf of Mexico. This includes about 0.95 million metric tons as nitrate and 0.58 million metric tons as organic nitrogen (Goolsby et al., 2001). The total amount of nitrogen load from the Mississippi River to the Gulf of Mexico has increased over the last 30 years; in particular, the nitrate load is three times greater than 30 years ago (Goolsby et al., 2001). The principle sources of nitrogen inputs include soil mineralization, fertilizer, legumes and pastures, animal manures, atmospheric deposition, and municipal and industrial point sources. The largest change in annual nitrogen input has been in fertilizer, which has increased more than six-fold since the 1950's. Five states (Illinois, Indiana, Iowa, Ohio and Minnesota) have the greatest amount of artificially drained soil, the highest percentage of total land in agriculture (corn and soybean) and the highest use of nitrogen fertilizers in the nation. The region has abundant precipitation most years for crop growth and only rarely suffers major yield declines because of drought.

**Water Quality Models**

Nonpoint source pollution complexities pose major challenges for scientists who are studying methods of improving water quality. One challenge is the lack of integrated, scientifically sound approaches to identify problems in watersheds and to predict the results of potential control actions. This necessitates using several techniques, models, or analytical tools in assessing different components of the complex watershed system. In this regard, simulation models are used extensively in water quality planning and pollution control. These models offer a sound scientific framework for watershed analyses of water pollutant movement. Integrated modeling systems link the models, data, and user interface within a single system. The United States Department of Agriculture Agricultural Research Service (USDA-ARS) and other agencies initiated the development of several process based water quality models over the past two decades, in response to the passage of the Clean Water Act in the early 1970s and growing awareness of agricultural nonpoint source pollution (NPS). These models were designed to provide guidance regarding best management practices (BMPs) that can help alleviate NPS pollution at the field- and river basin-scales.

One of the more widely used water quality models is the Soil and Water Assessment Tool (SWAT), which was developed to assess the water quality impacts of agricultural and other land use for a range of watershed scales including large river basins.

**SWAT Model**

The SWAT model was developed at the USDA Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas. SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. The models is physically based (models physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc.), uses readily available inputs (minimum data requirements), computationally efficient, and long-term continuous watershed scale simulation model. It operates on a daily time step. The model is a direct outgrowth of the SWRRB (Simulator for Water Resources in Rural Basins; Arnold et al., 1990) model and integrates functionalities of several other models such as CREAMS (Chemical, Runoff, and Erosion from Agricultural Management Systems; Knisel, 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems; Leonard et al., 1987), and EPIC (Erosion-Productivity Impact Calculator; Williams et al., 1984), allowing for the simulation of climate, hydrology, plant growth, erosion, nutrient transport and transformation, pesticide transport and management practices. Complete descriptions on model and different model components can be found in Arnold et al. (1998) and Neitsch et al. (2002).

The SWAT model is capable of simulating a high level of spatial details by allowing the watershed to be divided into a large number of subwatersheds. In SWAT, a watershed may be partitioned into multiple subwatersheds. The division is important when different areas of the watershed are dominated by land uses or soils dissimilar enough in properties to impact hydrology. Input information for each subbasin is grouped or organized into the following categories: climate, ponds/wetlands, groundwater, main channel/reach, and hydrologic response units (HRUs). HRUs are lumped land areas within the subwatershed that are comprised of unique land cover, soil, and management combinations. Flow generation, sediment yield, and non-point-source loadings from each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet.

Water balance is the driving force behind everything that happens in the watershed. To accurately predict the movement of sediment, nutrients or pesticides, the hydrologic cycle as simulated by the model must conform to what is happening in the watershed. Simulation of the hydrology of a watershed can be separated into two major divisions: land phase and routing phase. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each subwatershed. This phase includes climate, hydrology, plant growth, erosion, nutrients, pesticides, and management. The routing phase of the hydrologic cycle controls the movement of water, sediments, nutrients and pesticides through the channel network of the watershed to the outlet. This phase includes routing in the main channel and reservoirs.

The model has been widely used around the world. Previous applications of SWAT for flow and/or pollutant loadings have compared favorably with measured data for a variety of watershed scales (e.g., Rosenthal et al., 1995; Arnold and Allen, 1996; Srinivasan et al., 1998; Arnold et al., 1999; Saleh et al., 2000; Santhi et al., 2001).

**Hydrology**

The hydrology part of the model includes snowmelt, surface runoff, evapotranspiration, ground water percolation, lateral flow, and groundwater flow (or return flow). If the daily mean temperature is less than 0°C, it is assumed that precipitation falls as snow. Snow is assumed to melt on days when the maximum temperature exceeds 0°C. The water balance of each HRU in SWAT is represented by four storage volumes: snow, soil profile (0-2m), shallow aquifer (typically 2-20m), and deep aquifer (>20m). Flow generation, sediment yield, and non-point-source loadings from each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet. Hydrologic processes are based on the water balance equation:

$$SW_t = SW + \sum_{t=1}^{t} (R_i - Q_i - ET_i - P_i - QR_i) \qquad (1)$$

where *SW* is the soil water content minus the wilting-point water content, and *R*, *Q*, *ET*, *P*, and *QR* are the daily amounts (in mm) of precipitation, runoff, evapotranspiration, percolation, and groundwater flow; respectively.

The soil profile is subdivided into multiple layers that support soil water processes including infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers. The soil percolation component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Downward flow occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. Percolation from the bottom of the soil profile recharges the shallow aquifer. If temperature in a particular layer is 0°C or below, no percolation is allowed from that layer. Lateral subsurface flow in the soil layer (0-2 m) is calculated simultaneously with percolation. A kinematic storage routing technique that is based on slope, slope length, and saturated conductivity is used. Percolation from the bottom of the root zone is assumed to recharge a shallow aquifer. The shallow aquifer is then simulated as the source of groundwater flow contributions to stream flow (Arnold et al., 1993). A recession constant is used to lag flow from the aquifer to the stream.

Partitioning of daily precipitation between surface runoff and infiltration is estimated with a modification of the SCS Runoff Curve Number (CN) method (Mockus, 1969). Partitioning of snowmelt between runoff and percolation is treated in the same manner as precipitation with the CN method.

Three methods are available to model potential evapotranspiration: Pristley-Taylor, Hargreaves, and Penman-Monteith. A modified version of the Penman-Monteith method is used in SWAT that accounts for the effects of changing atmospheric $CO_2$ in the transpiration computations based on the methodology described by Stockle et al. (1992). The Penman-

Monteith method requires solar radiation, air temperature, wind speed, humidity, and vegetation parameters as input. The model computes evaporation from soils and plants separately. Actual soil water evaporation is estimated using exponential functions of soil depth and water content. Plant water evaporation is simulated as a linear function of potential ET, leaf area index and root depth and can be limited by soil water content.

**Fate and Transport of Nitrogen**

SWAT tracks the movement and transformations of several forms of nitrogen in the watershed. In the soil, transformations of nitrogen and phosphorus from one form to another are governed by the nitrogen cycle. Nutrients may be introduced to the main channel and transported downstream through surface runoff, lateral subsurface flow, and groundwater flow.

The three major forms of nitrogen in soils are organic nitrogen (associated with humus), mineral nitrogen (held by soil colloids), and mineral nitrogen (in solution). Nitrogen may be added to the soil by fertilizer, manure, residue application, rain, or fixation by symbiotic or nonsymbiotic bacteria. Nitrogen is removed from the soil by plant uptake, leaching, volatilization, denitrification, and erosion.

SWAT monitors five different pools of nitrogen in the soil as shown in figure 1. Two pools are inorganic forms of nitrogen, $NH_4^+$ and $NO_3^-$, while the other three pools are organic forms of nitrogen. Fresh organic N is associated with crop residue and microbial biomass while the active and stable organic N pools are associated with the soil humus. The organic nitrogen associated with humus is partitioned into two pools to account for the variation in availability of humic substances to mineralization. Nitrate may transported with surface runoff, lateral flow or percolation. To calculate the amount of nitrate moved with water, the concentration of nitrate in the mobile water is calculated. This concentration is then multiplied by the volume of water moving in each pathway to obtain the mass of nitrate lost from the soil layer.

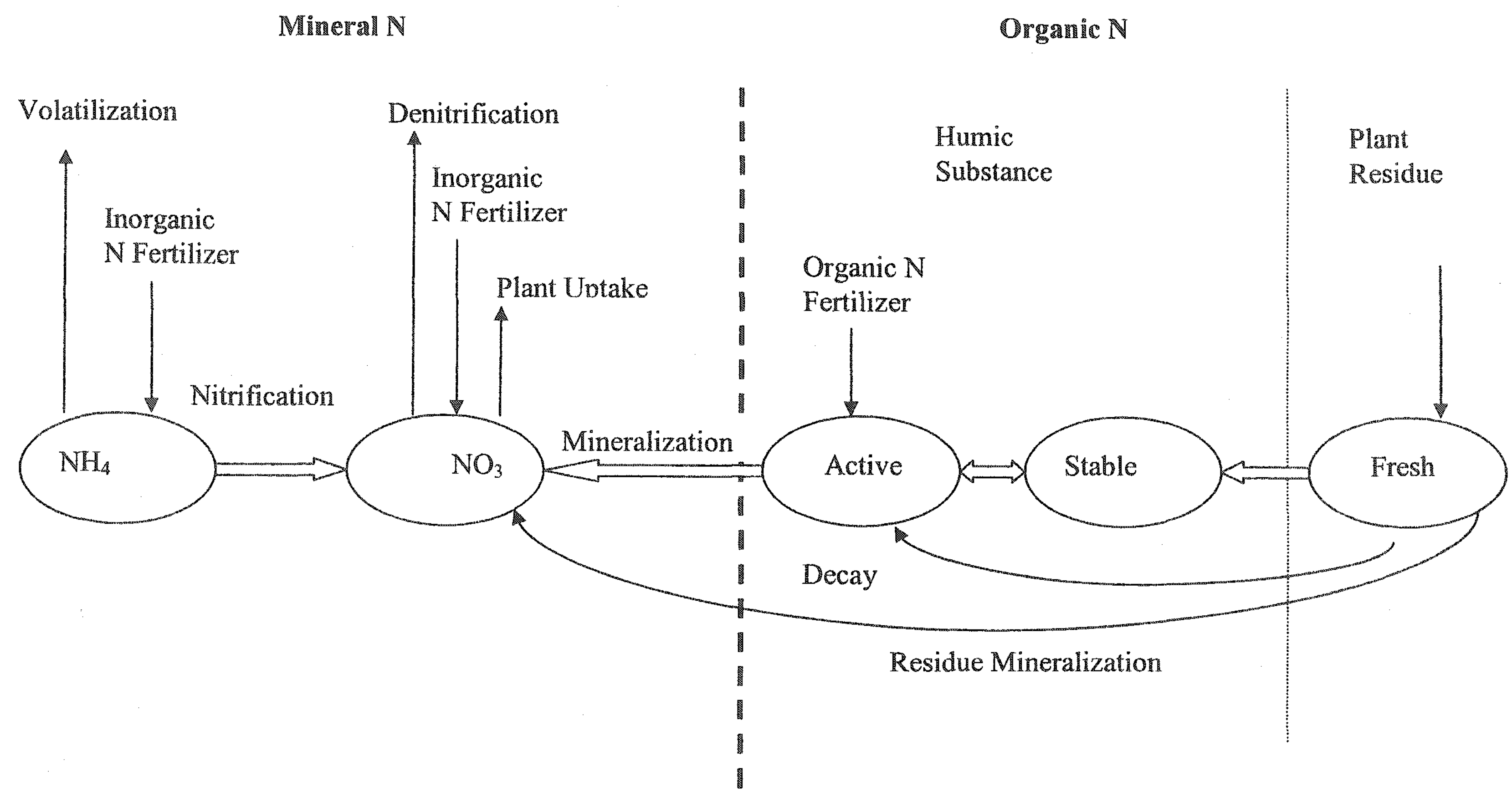


Figure 1. Nitrogen cycle

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# CHAPTER 3. EVALUATION OF SWAT MODEL FOR THREE IOWA MANAGEMENT SYSTEMS

## Part I: Tile Flow[1]

A paper submitted to Transaction of the ASAE

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**Abstract**

Using a model as a management tool requires testing of the model against field measured data prior to its application for solving natural resource problems. This study was designed to calibrate and evaluate the subsurface drainage component of the Soil Water Assessment Tool (SWAT) model version 99.2 for three management systems at a research site near Nashua, Iowa: continuous corn - chisel plow, corn-soybean - no-till and soybean-corn - no-till. Each system was analyzed for two different research plots that varied in soil type and slope gradient. Calibration was performed with 1995 measured tile drain flows, while validation was carried out using measured tile drain flows for 1993-1994 and 1996-1997. In general SWAT adequately tracked the measured tile drain flows, except that the

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cumulative monthly tile flows were consistently under-predicted. Differences of 2 to 11% and model efficiencies ranging between 0.47 to 0.67 were determined for the annual simulated tile flows as compared to the corresponding measured flows for the validation period. The $r^2$ values determined for the simulated monthly tile drain flows ranged from 0.70 to 0.97 for the calibration period and 0.49 to 0.67 for the validation period. The overall evaluation of SWAT 99.2 indicates that the model has the capability of predicting annual subsurface flows satisfactorily for different soil types, slopes and weather conditions. However, further research is needed to better quantify why SWAT is under-predicting the cumulative monthly tile flows.

**Keywords:** modeling, tile drainage, nitrate, crop rotation, tillage, water quality, field monitoring.

## Introduction

Artificial subsurface drainage is required to maintain the productivity of poorly drained soils and is practiced on over 30% of the soils in the Midwestern USA (Hatfield, 1998). Agrochemicals and other fertilizer sources such as manure are extensively used in the region to increase crop production, but are also significant nonpoint sources of groundwater and surface water pollution. Subsurface tile drains are key pollution pathways to surface water, especially for nitrate-nitrogen ($NO_3$-N), as reported by Kanwar et al. (1999), Jaynes et al. (1999) and Cambardella et al. (1999). The subsurface flow response of a given soil system can be influenced by soil type, agricultural management practices, rainfall pattern, and topography. Tillage practices directly affect the soil water properties of the surface soil and soil leaching characteristics (Kanwar et al., 1988). Tillage practices can also influence the distribution and continuity of macropores that can act as preferential pathways for rapid movement of water and chemicals to the groundwater (Singh et al., 1991). Therefore it is necessary to understand the factors that affect chemical transport and fate.

Best management practices (BMPs) are technically feasible methods for preventing or reducing nonpoint source pollution to a level compatible with water quality goals (Novotny and Olem, 1994). The evaluation and assessment of BMP impact can be accomplished in two ways: (1) by collecting field data over an extended time period, or (2) by using computer simulation models developed from current scientific knowledge. Long-term monitoring of BMP impacts is essential to assess their effectiveness under different conditions. However, it is impractical to monitor all BMPs under all conditions due to time and cost constraints. Computer simulation models provide an alternative to evaluate the response of soil and crops to a range of management practices in an efficient and cost effective way (Bakhsh et al., 1999; Zacharias and Heatwole, 1994). Nevertheless, testing and evaluation of computer models require the use of extensive field data to ensure that they are reliable for the prediction of management effects.

Numerous models have been developed that vary in complexity for simulating flow, and in some cases agricultural chemical movement, through soil. Some of these models are specifically designed to simulate tile drain processes. Kirkham (1985) developed an analytical solution for steady-state flow to parallel tile drains in a homogeneous soil underlain by an impermeable layer. Dutt et al. (1972) and Duffy et al. (1975) developed mathematical models of biophysio-chemical processes that could be applied to tile-drained agriculture areas. Scotter et al., (1990) developed a simple numerical model for transient soil water flow to a tile drain for assumed or measured values of rainfall, evaporation, deep percolation, drain spacing, and depth. The DRAINMOD model (Skaggs 1981) was developed to support design and evaluation of different drainage systems included tile drains. The DRAINMOD-N model (Brevé et al., 1997) is an adaptation of DRAINMOD that also simulates $NO_3$-N movement through tiles.

Other models have been developed that focus on surface runoff and leaching of water and agricultural chemicals rather than tile flow processes. The Chemical, Runoff, and Erosion From Agricultural Management Systems (CREAMS) model (Knisel, 1980) was designed to simulate the long-term impact of land management on water leaving the edge of a field. Several others models that are based on CREAMS include the Ground Water Loading Effects on Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987), the Simulator for Water Resources in Rural Basins (SWRRB) model (Williams et al., 1985), the Erosion-Productivity Impact Calculator (EPIC) model (Williams et al., 1990) and the Agricultural Non-point Source (AGNPS) model (Young et al., 1989).

The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Srinivasan et al., 1998) is a relatively new model, that is based in part on functions used in SWRRB and other previously developed models, to predict the effects of different management scenarios on water quality, pollutant loadings and sediment yields by accounting for variation in soil, climate, and land use across a watershed or river basin. Previous applications of SWAT have compared favorably with measured data for a variety of watershed scales (Srinivasan and Arnold, 1994; Rosenthal et al., 1995; Arnold and Allen, 1996; Srinivasan et al.,1998; Arnold et al., 1999; Saleh et al., 2000). SWAT was selected for this study due to its flexibility in handling a wide range of management scenarios and environmental conditions including tile-drained cropland. It was also chosen because of its ability to simulate large watersheds, which is a goal of future modeling research. The goal of this study was to calibrate and evaluate the subsurface drainage component of SWAT version 99.2 by using tile flow data collected during 1993-97 at a research site located in northeast Iowa near Nashua, Iowa. The specific objectives of this research were to:

1. Calibrate the tile flow component of SWAT by using measured tile flow data from 1995 for different management systems.
2. Evaluate the performance of SWAT for the same systems for1993-94 and 1996-97 by comparing the predicted tile flows with corresponding field-measured values.

## Model Description

The SWAT model was developed by modifying the predecessor SWRRB model and is designed to assist water resource managers in assessing the impact of management on water supplies and non-point source pollution. Key modifications include the addition of lateral subsurface flow and ground water flow components. A complete description of SWAT model components is found in Arnold et al. (1998); a brief description is provided here.

### General Hydrology

SWAT consists of three major components: sub basin, reservoir routing, and channel routing. The sub basin component consists of eight main subcomponents defined as hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, agricultural management, and pesticides. The hydrology subcomponent is comprised of surface runoff, percolation, lateral subsurface flow, groundwater flow, snow melt, evapotranspiration (ET), transmission losses, and ponds. Surface runoff is predicted for daily rainfall by using the SCS curve number equation (Mockus, 1969). The curve number varies non-linearly from condition 1 (dry) at wilting point to condition 3 (wet) at field capacity, and approaches 100 at saturation.

The local water balance of SWAT is represented by four storage volumes: snow, soil profile (0-2 m), shallow aquifer (2-20 m) and deep aquifer (>20 m). The soil profile can be divided into multiple layers. Soil water processes include infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers. The percolation of SWAT uses a storage routing technique to predict flow through each soil layer. Downward flow occurs when field capacity of the soil layer is exceeded and if the layer below is not saturated. The downward flow rate is governed by the saturated hydraulic conductivity of the soil layer. Percolation from the bottom of the soil profile recharges the shallow aquifer. Ground water flow contribution to total stream flow is simulated by routing a shallow aquifer storage component to the stream (Arnold et al., 1998). Upward flow may occur when the field capacity of the next lower layer is exceeded. Movement from a lower layer to an adjoining upper layer is governed by the soil water to field capacity ratios of the two layers. Percolation is also affected by the soil temperature. No percolation is allowed from a layer if the temperature of that layer is 0° C or below. If snow is present, it is melted on days when the maximum temperature exceeds 0° C. Melted snow is treated the same as rainfall for estimating runoff and percolation.

Three options are offered in SWAT for estimating potential ET: Hargreaves (Hargreaves and Smani, 1985), Priestley-Taylor (Priestley and Taylor, 1972), and Penman-Monteith (Monteith, 1965). The Penman-Monteith method was used for this study, which requires solar radiation, air temperature, wind speed, and relative humidity as inputs. The model computes evaporation from soils and plants separately. Potential soil water evaporation is estimated as a function of potential ET and leaf area index (area of plant leaves relative to the soil surface area). Actual soil evaporation is estimated by using exponential functions of soil depth and water content. Plant evaporation is simulated as a linear function of potential ET, leaf area index, and root depth and can be limited by soil water content. It is assumed that 30% of the total plant water uptake comes from the upper 10% of the root zone and that the roots can compensate for water deficit in some layers by using more water in layers with adequate supplies.

**Subsurface Tile Flow**

Water in the soil can flow under saturated or unsaturated conditions. In saturated soils, flow is driven by gravity and usually occurs in the downward direction. Unsaturated flow is caused by gradients arising due to adjacent areas of high and low water content. Unsaturated flow may occur in any direction. SWAT directly simulates saturated flow only. The model records the water contents of the different soil layers but assumes that the water is uniformly distributed within a given layer. This assumption eliminates the need to model unsaturated flow in the horizontal direction. Unsaturated flow between layers is indirectly modeled with the depth distribution of plant water uptake and the depth distribution of soil water evaporation.

Saturated flow occurs when the water content of a soil layer surpasses the field capacity for the layer. Water in excess of field capacity is available for percolation, lateral flow or tile flow drainage. The amount of water that moves from one layer to the underlying layer is calculated using a storage routing methodology. The travel time for each layer is unique.

To simulate the tile drainage, the user must specify the depth from the soil surface to the drain, the amount of time required to drain the soil to field capacity, and the amount of lag between the time water enters the tile until it exits the tile and enters the main channel. Tile drainage occurs when the soil water content exceeds the field capacity in the soil layer where the tile drains are installed. The amount of water entering the drain on a given day is calculated with the equation:

$$q_{tile} = (SW_{ly} - FC_{ly})(1 - e^{(\frac{-24}{t_{drain}})}) \qquad \text{if} \quad SW_{ly} > FC_{ly} \tag{1}$$

where $q_{tile}$ is the amount of water removed from the layer on a given day by tile drainage (mm) , $SW_{ly}$ is the soil water (mm) content of the layer on a given day, $FC_{ly}$ is the field capacity (mm) of the layer, and $t_{drain}$ is the time required to drain the soil to field capacity (hr). Water entering the tiles is treated like lateral flow.

In large subbasins with a time of concentration greater than 1 day, only a portion of the tile/lateral flow will reach the main channel on the day it is generated. SWAT incorporates a tile/lateral flow storage feature to lag a portion of tile/lateral flow release to the main channel.

Once the tile/lateral flow is calculated, the amount of tile/lateral flow released to the main channel is calculated as:

$$q_t = \left(q_{tile} + q_{tstor,i-1}\right)\left(1 - e^{-\frac{24}{tile_{lag}}}\right) \quad (2)$$

where $q_t$ is the amount of tile/lateral flow discharged to the main channel on a given day (mm), $q_{tile}$ is the amount of tile/lateral flow generated in the subbasin on a given day (mm), $q_{tstor,i-1}$ is the tile/lateral flow stored or lagged from the previous day (mm), and $tile_{lag}$ is the drain tile lag time (hr). Lagging the tile flow affects the timing (and thus the daily peaks) but not the total tile flow volume.

**Experimental Site Description and Observed Tile Flow Data**

Observed tile flow data were collected during 1993-97 from a research site at Iowa State University's Northeast Research Center (NERC) near Nashua, Iowa. The plots at this study site are located on Kenyon, Readlyn, and Floyd soils with 2 to 3% organic matter. Kenyon is classified as a fine-loamy, mixed mesic, Typic Hapludoll; Readlyn as a fine loamy, mixed mesic Aquic Hapludoll; and Floyd as a fine loamy, mixed, mesic Aquic Hapludoll. These soils have seasonally high water tables, benefit from subsurface drainage, and are classified as hydrologic group B. The site has 36, 0.4-ha experimental plots with fully documented tillage and cropping records. Long-term tillage studies (three replications of each tillage treatment) were initiated at this site in 1979 to evaluate the effects of different management systems on subsurface drainage water quantity and quality. Tile lines were installed about 1.2-m deep at a 28.5-m spacing in 1979. Each plot has one tile line passing through the middle of the plot and there is a tile line at each of the plot borders. The middle tile lines of all the plots were intercepted and connected to individual sumps for measuring subsurface drainage and collecting water samples for chemical analysis. A detailed description of the automated subsurface drain-monitoring system is given by Kanwar and Baker (1991).

For this study, the following treatments were simulated for 1993-97 for six of the 0.4 ha plots (Table 1): (1) continuous corn - spring chisel plow (CC-CP), (2) soybean-corn - no-till (SC-NT) with soybean planted in 1993, and (3): corn-soybean - no-till (CS-NT) with corn planted in 1993. These treatments included most of the tillage and cropping system combinations that were studied at the Nashua site during 1993-97.

## Model Input Data

### Climate

Daily values of precipitation, maximum and minimum air temperature, wind speed, solar radiation, and relative humidity are required for SWAT. If measured daily precipitation and maximum/minimum air temperatures are available, they can be input directly to SWAT. If not, they can be generated within SWAT with a weather generator. For this study, precipitation and temperature data measured at the Nashua site were input for the entire five-year period. Daily solar radiation, wind speed, and relative humidity are always generated in SWAT 99.2; monthly weather statistics for Osage, Iowa, located approximately 50 km from the study site, were used to generate these inputs for this study.

### Soil Properties

The soil data used by SWAT can be divided into two groups: physical characteristics and chemical characteristics. The physical properties of the soil govern the movement of water and air through the profile and have a major impact on the cycling of water within the hydrologic response unit (HRU). Inputs for chemical characteristics are used to set initial levels of different chemicals in the soil. Input data for the physical properties are required; chemical property data is optional. The model requires the division of the soil profile into horizons. For this study, the kenyon, readlyn, and floyd soil profiles were each divided into six soil horizons. The soil data input into the model were adapted from Singh et al. (1996) and are based on measurements made at the experimental site. Table 2 lists selected soil properties, as a function of horizon, that were input into SWAT for the three soils included in this study.

**Land Management**

The model requires data for planting, harvest, irrigation application, nutrient application, pesticide application, and tillage operations. Management information for each treatment is given in Table 3. The tillage component of SWAT was designed to incorporate and redistribute surface residues, nutrients, and pesticides into the soil, within the portion of the soil affected by the mixing depth of the tillage implement. The user inputs the day of the tillage operation and selects a tillage implement from a tillage implement file. Each implement has as an associated mixing efficiency (0-100%) which determines how much of the surface residue is buried by the tillage implement pass. No other adjustments to the soil profile (e.g., changes in bulk density) are simulated by SWAT in response to tillage.

**Calibration Procedure**

The model was calibrated and evaluated using experimental data from the six different plots on a plot-by-plot basis for the 1995 growing season, which was chosen to be the calibration period because the precipitation levels were close to the long-term average for the site. The criterion used for calibrating the model was to minimize the difference between measured and simulated cumulative annual tile flow and to match the simulated monthly cumulative tile flow with the measured values. A trial and error procedure was used to determine the best values of two variables: (1) the soil evaporation compensation coefficient (esco), and (2) the condition II runoff curve number (CN2). The CN2 calibration affected the magnitude of the annual tile flow while the esco calibration impacted the monthly and annual tile flow values.

The process was initiated by calibrating the esco values so that the monthly simulated tile flows matched the observed tile flow values as closely as possible. The resulting esco values were allowed to vary between 0.75 and 1.0. As the value for esco was reduced, the model was able to extract more evaporative demand from lower levels. The procedure was continued until the simulated and observed monthly tile flow values were in close agreement and the simulated cumulative annual flows were within 10% of the observed total annual tile flows. The calibrated esco values ranged from 0.76 to 0.91 (Table 4) and are higher for the CS-NT and SC-NT plots relative to the CC-CP plots.

Further calibration was performed by adjusting the CN2 values for each plot, resulting in the values listed in Table 4. These adjusted CN2 values are 9 to 18% below the standard curve number of 78 as given by Mockus (1969), which represents row crops grown in hydrologic group B soils consisting of good hydrologic conditions. Specific conditions at the Nashua site point to the need for reduced CN2 values. First, little surface runoff has been observed for the 36 plots at the site, resulting in high infiltration rates that approach 2.5 cm $hr^{-1}$. These characteristics suggest that the soils at the site may more closely reflect hydrologic group A conditions, with a base CN2 of 72, rather than the B hydrologic group that is normally assigned to these soil types. Rawls et al. (1980) and Rawls and Richardson (1983) found that CN2 values should be reduced by up to 10% for conservation tillage and no-till systems; thus, further reductions in the CN2 values would be expected based on the types of tillage systems that were used for the six plots. Reduction of the CN2 values for soybeans can also be further justified based on the fact that the soybeans were drilled in closely seeded rows 20 cm apart, resulting in a dense crop canopy that is more reflective of a closely seeded legume crop than a row crop. The CN2 reductions that resulted from the SWAT calibration are greater than those reported by Chung et al. (2002) for simulations performed with the EPIC model for the Nashua site.

The CN2 values for CC-CP plots were lower as compared to no-till plots (Table 4), similar to the trends found for the ESCO values. Within the same management systems, the calibrated CN2 values were higher for the plots with higher slopes. A higher CN2 value implies greater surface runoff; thus the higher CN2 values for higher slopes within a given management system is consistent with expectations.

A final calibration step focused on adjusting the available water content (AWC) levels at the start of the 1995 calibration year and at the start of 1993, the beginning of the validation period. The moisture content fluctuated in each soil layer in response to the precipitation inputs, which had a significant effect on the tile flows. The soil moisture level of the top layer was especially critical because it affected both the tile flows and the ET rates.

Lower soil moisture levels in the top soil layer resulted in lower percolation rates and correspondingly greater evaporation losses to the atmosphere. Thus adjustment of the AWC levels at the start of the calibration and validation phases was necessary to achieve the best match between the simulated and measured tile flows. The initial AWC levels for 1993 and 1995 were first set equal to the difference between the field capacity and wilting point (standard AWC definition), but were ultimately further adjusted to ensure that the simulated tile flows started at approximately the same time as the observed flows. A sensitivity analysis was also performed to assess the impact of varying the $t_{drain}$ parameter used in equation 1, between 24 and 96 hours. The results of the analysis indicated that the choice of value for the $t_{drain}$ parameter did not greatly affect the predicted tile flows.

**Model Evaluation Criteria**

To test the ability of the model to predict system response, the model was evaluated with measured subsurface drain flow data for 1993-94 and 1996-97 for all three tillage-cropping systems, again on plot-by-plot basis. The validation runs were performed for the complete five-year period that included 1995 rather than in two two-year time periods. The coefficient of determination ($r^2$), Nash-Sutcliffe model efficiency (E), and the deviation of the tile flow volume ($D_v$) were the performance indicators used to judge the model prediction capability. The $r^2$ and E statistics were used to evaluate the monthly flow results while the $D_v$ was used to assess the accuracy of the predicted annual and annual average tile flows. The $r^2$ represents the percentage of the variance in the measured data that is explained by the simulated data and varies between 0 and 1. A perfect fit between the measured and simulated data occurs when the $r^2$ value equals 1, the intercept equals zero, and the slope equals 1; i.e., there is a perfect match along the 1:1 line.

The E statistic indicates how close the plot of the simulated versus observed values come to the 1:1 line (Nash and Sutcliffe, 1970) and is calculated using

$$E = \frac{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2 - \sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2} \qquad (3)$$

Where $O_i$ and $P_i$ are the observed and predicted values, $\bar{O}$ is the mean of the observed values, and i is the number of samples. The E can range from $-\infty$ to 1, with 1 indicating a perfect fit.

Another goodness of fit criterion is the deviation of tile flow volume ($D_v$). A lower $D_v$ value indicates a better fit, and the value 0.0 represents the perfect simulation of observed volume (ASCE, 1993). The $D_v$ value is given by the equation

$$D_v = \frac{V_{simu} - V_{obs}}{V_{obs}} * 100\% \qquad (4)$$

Where $V_{obs}$ and $V_{simu}$ are the measured and simulated yearly or seasonal tile flow volumes, respectively.

**Results and Discussion**

The amount of observed annual tile drainage flows were clearly a function of the total annual precipitation. The maximum tile flow volume was observed in 1993 for all plots, which had the highest precipitation (1026.32 mm; 26% > normal) recorded during the five-year study period. In contrast, the minimum tile flow volume occurred in 1996, a year with only 660.12 mm of precipitation (19% < normal). The observed tile flows in April 1993 (Figures 1-3) actually exceeded the amount of precipitation that was recorded at Nashua for that month. This occurred because of snowmelt water that infiltrated the soil profile in March and later entered the tiles in April.

The $r^2$, E, and $D_v$ values determined for the calibration year for six plots are shown in Table 5. The $r^2$ values ranged from 0.70 to 0.97 (Table 5), indicating a strong correlation between the predicted and measured monthly flows. Standard errors were also computed for the slope and intercept components of the regressions (Table 6). T-tests performed using these standard errors indicated that the slopes and intercepts determined for the simulated flows for each plot were all significantly different from a slope of 1 and an intercept of zero, respectively. The t-test results reveal that the simulated values differed significantly from the 1:1 line, and suggest that the predicted values were weaker than what the $r^2$ values indicate. The E values computed for 1995 were somewhat weaker, ranging from 0.52 to 0.68, but still indicate that the model captured much of the observed monthly flow trends. The predicted annual tile flows for the calibration year (Table 5) accurately reflected the observed values, as indicated by the relatively low $D_v$ values that ranged from –8.4 to 6. However, a clear pattern of under-prediction is indicated for the annual flows estimated by SWAT for the majority of the plots.

Table 6 shows the cumulative observed and predicted annual tile flow volumes, and the corresponding $D_v$ results, for all five years. The predicted annual tile flow amounts for the four validation years were less accurate than the calibration year, especially for 1996 for which the $D_v$ values ranged from –13.1 to 29.6. However, the $D_v$ values calculated for the annual predicted flows for the four validation years (Table 7) reveal that these four-year annual flows were closer to the corresponding measured flows as compared to the 1995 calibration year, except for the plot 15 simulations. The $r^2$ and E values determined for the four-year validation period ranged from 0.49 to 0.67 and 0.47 to 0.67, respectively (Table 7). These statistics clearly reveal that the correlation between the predicted and measured monthly flows were not as accurate for the validation period as compared to the calibration year. In addition, t-tests performed for all six plots across the four-year validation period (Table 9) showed that the standard errors computed for the simulated regression slopes and intercepts were again significantly different from a slope of 1 and an intercept of 0.However, the validation period $r^2$ and E values do show that SWAT was able to track much of the measured monthly flow trends over the four- years that were simulated.

The simulated and observed cumulative annual values show that the largest tile flows occurred for the CC-CP system in most years, followed by the SC-NT system. The higher tile flows estimated for CC-CP reflect lower CN2 values that were used for that system (Table 4). Also, the CC-CP and SC-NT plots with the highest slopes had the greatest predicted and observed tile flows, within each respective management system, for both the calibration year of 1995 (Table 5) and also for the four validation years (not shown). These trends run counter to expectations and indicate the possibility that spatial variability exists in the soil properties within the individual plots, which SWAT would not be able to simulate. The trends also suggest that at least some of the plots may not be totally hydrologically isolated; i.e., subsurface flow may be occurring between plots that impacted the observed tile flow values from these plots.

Time series analyses of predicted and observed monthly flows, monthly precipitation totals, and scattergram comparisons between the predicted and measured monthly values are shown in Figures 1-3 for plot 21 (CC-CP), plot 29 (SC-NT), and plot 24 (CS-NT). The time series comparisons indicate that SWAT generally tracked the measured flows for each plot. However, the time series results clearly show that most of the cumulative monthly flows were under-predicted by roughly a factor of two and that SWAT tended to predict some flow in months that were observed to have no flows. The scattergrams in Figures 1-3 show the predicted versus measured monthly flows relative to a 1:1 line for the full five-year period. Some of the points deviated considerably from the 1:1 line, especially for plot 29. Several of the simulated values are also shown on the y-axis in each scattergram, underscoring again the fact that the model predicted small amounts of flow during periods in which no flow occurred.

The under-estimation of the monthly flows by SWAT could be due in part to the fact that macropore flow was not simulated, which may have been a key component of the observed peak flows. Observed peak tile flows usually occurred within the same day that a major rainfall event occurred, indicating preferential movement of water through macropores. Bjorneberg et al. (1996) estimated the time to peak flow from an 0.5 ha area to be about 6 hours following the start of a major rainfall event for this site. On average, the highest peak tile flows occurred for the no-till systems at the Nashua site regardless of cropping system. Large peak flows occur for no-till conditions because macropores (worm or root holes and other natural crack features) are typically not destroyed or disturbed (Kanwar et al., 1997). Under-prediction of the daily peak flows for these conditions will in turn result in under-prediction of the monthly flows.

**Summary and Conclusions**

The ability of the SWAT model (version 99.2) to simulate tile flow was assessed by simulating three different combinations of management and cropping systems over a five-year period (1993-97) for six different research plots at Nashua, Iowa. The model was calibrated by minimizing the difference between the 1995 predicted and observed cumulative and monthly tile flows. The calibration process mainly involved adjusting the esco and CN2 parameters but also included some adjustments in the AWC levels. The 1995 predicted cumulative annual tile flows differed from the measured flows by 8% or less; there was a clear pattern of under-prediction across most of the plots. The $r^2$ values computed for the 1995 simulated monthly flows versus the corresponding measured flows were relatively robust, ranging from 0.70 and 0.97. However, further statistical analysis of the slopes and intercepts determined for the calibration regressions revealed that the predicted monthly flow trends differed significantly from the corresponding measured flows. The E values computed for the calibration year ranged between 0.52 and 0.68, indicating that model was able to generally track the measured flow trends.

Validation of SWAT was performed by predicting the tile flows for a total of four years: 1993-94 and 1996-1997. The cumulative annual tile flows were again under-predicted by SWAT for most of the management-plot combinations, although almost all of the resulting four-year average $D_v$ values were more accurate then the corresponding 1995 $D_v$ values. The simulated tile flows followed the trends of observed flows reasonably well for the validation period, but the $r^2$ (0.49 to 0.67) and E (0.47 to 0.67) values were weaker than those determined for the calibration period. Further statistical analysis of the regression slopes and intercepts for the four-year period showed again that the simulated results deviated significantly from the 1:1 line.

The model under-estimated the monthly flows and predicted low levels of flow to occur during periods in which no flow was observed. The under-estimation of the peak flows could be due to the fact that macropore flow is not accounted for in SWAT. Observations at the site indicate that macropore flow may be an important component of peak flow periods. Higher observed and predicted tile flows occurred under plots with higher slopes, relative to plots with lower slopes with the same management, for the CC-CP and SC-NT systems. This result was somewhat inconsistent with expectations and suggests that there is probably significant spatial variability in soil properties within individual plots and that subsurface flow between plots may be affecting the measured flows.

Overall, the evaluation of SWAT 99.2 for the Nashua conditions revealed that the model was relatively weak in its ability to replicate much of the measured tile flow patterns. Further research is needed to better quantify why SWAT is under-predicting the cumulative monthly tile flows and over-predicting monthly flow during the periods in which little or no flow was occurring. Saleh et al. (2003) report good agreement between simulated and measured tile flows for the Walnut Creek Watershed located in central Iowa, using an experimental version of SWAT with improved tile flow and related components. Future research at Nashua will be conducted with a version of SWAT that contains these enhanced routines.

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Table 1. Soil type, mangement practice, and slope for six study plots

| Plot No. | Soil Type | Crop-Tillage[a] | Slope (%) |
|---|---|---|---|
| 21 | Readlyn | CP,CC | 3.2 |
| 26 | Floyd | CP,CC | 4.4 |
| 15 | Readlyn | NT,SC | 1.1 |
| 29 | Kenyon | NT,SC | 3.2 |
| 24 | Kenyon | NT, CS | 1.6 |
| 28 | Kenyon | NT,CS | 3.6 |

[a]CC-CP = continuescorn - Chisel plow; SC-NT = soybean corn - notill;
CS-NT = corn-soybean -no-till

Table 2 . Selected soil layers properties for Kenyon, Floyd, and Readlyn soils

| Horizon No. | Depth mm | Bulk Density $Mg/m^3$ | Organic Carbon % | Particle size distribution, % Clay | Silt | Sand | Hydraulic Conductivity mm/hr |
|---|---|---|---|---|---|---|---|
| **Kenyon Soil** | | | | | | | |
| 1 | 0-20 | 1.36 | 2.00 | 22 | 42 | 38 | 20.91 |
| 2 | 20-400 | 1.53 | 2.00 | 25 | 34 | 41 | 20.17 |
| 3 | 400-500 | 1.55 | 0.90 | 24 | 32 | 42 | 19.71 |
| 4 | 500-800 | 1.65 | 0.60 | 29 | 28 | 44 | 17.26 |
| 5 | 800-1200 | 1.70 | 0.40 | 25 | 25 | 44 | 13.45 |
| 6 | 1200-1500 | 1.75 | 0.20 | 25 | 25 | 44 | 10.95 |
| **Floyd Soil** | | | | | | | |
| 1 | 0-20 | 1.29 | 2.90 | 27 | 44 | 30 | 23.50 |
| 2 | 20-400 | 1.40 | 1.00 | 26 | 42 | 33 | 20.65 |
| 3 | 400-500 | 1.45 | 0.90 | 24 | 22 | 54 | 19.71 |
| 4 | 500-800 | 1.45 | 0.30 | 25 | 29 | 47 | 15.69 |
| 5 | 800-1200 | 1.58 | 0.20 | 24 | 40 | 35 | 13.14 |
| 6 | 1200-1500 | 1.70 | 0.20 | 24 | 40 | 35 | 10.95 |
| **Readlyn Soil** | | | | | | | |
| 1 | 0-20 | 1.34 | 2.40 | 26 | 43 | 31 | 22.95 |
| 2 | 20-400 | 1.45 | 2.40 | 25 | 43 | 31 | 20.17 |
| 3 | 400-500 | 1.45 | 0.90 | 25 | 38 | 37 | 20.17 |
| 4 | 500-800 | 1.50 | 0.80 | 21 | 24 | 55 | 14.30 |
| 5 | 800-1200 | 1.65 | 0.30 | 25 | 28 | 46 | 13.45 |
| 6 | 1200-1500 | 1.70 | 0.30 | 24 | 28 | 46 | 10.95 |

Table 3. Operations simulated for three tillage and crop rotation systems

| | CC-CP | | CS-NT | | SC-NT | |
|---|---|---|---|---|---|---|
| **Year** | **Date** | **Operation** | **Date** | **Operation** | **Date** | **Operation** |
| 1993 | 5/14 | Elem-N (135 Kg/ha) | 5/17 | Elem-N (28 Kg/ha) | 5/26 | Plant soybean |
| | 5/3 | Chisel plow | 5/17 | Plant corn | 10/7 | Harvest soybaen |
| | 5/17 | Plant corn | 7/21 | Elem-N (144 kg/ha) | | |
| | 7/21 | Row Cultivator | 10/21 | Harvest corn | | |
| | 10/25 | Harvest corn | | | | |
| 1994 | 4/24 | Elem-N (135 Kg/ha) | 5/17 | Plant soybean | 5/2 | Elem-N (28 Kg/ha) |
| | 5/1 | Chisel plow | 10/6 | Harvest soybaen | 5/2 | Plant corn |
| | 5/2 | Plant corn | | | 6/17 | Elem-N (169 kg/ha) |
| | 6/2 | Row Cultivator | | | 10/25 | Harvest corn |
| | 9/28 | Harvest corn | | | | |
| 1995 | 5/12 | Elem-N (135 Kg/ha) | 5/16 | Elem-N (28 Kg/ha) | 5/12 | Plant soybean |
| | 5/15 | Chisel plow | 5/16 | Plant corn | 10/11 | Harvest soybaen |
| | 5/16 | Plant corn | 6/22 | Elem-N (193 kg/ha) | | |
| | 6/14 | Row Cultivator | 10/22 | Harvest corn | | |
| | 9/22 | Harvest corn | | | | |
| 1996 | 5/3 | Elem-N (135 Kg/ha) | 5/30 | Plant soybean | 5/21 | Elem-N (28 Kg/ha) |
| | 5/20 | Chisel plow | 10/8 | Harvest soybaen | 5/21 | Plant corn |
| | 5/21 | Plant corn | | | 6/24 | Elem-N (195 kg/ha) |
| | 6/24 | Row Cultivator | | | 10/21 | Harvest corn |
| | 10/21 | Harvest corn | | | | |
| 1997 | 5/12 | Elem-N (135 Kg/ha) | 5/12 | Elem-N (28 Kg/ha) | 5/16 | Plant soybean |
| | 5/12 | Chisel plow | 5/12 | Plant corn | 10/10 | Harvest soybaen |
| | 5/12 | Plant corn | 6/19 | Elem-N (125 kg/ha) | | |
| | 6/19 | Row Cultivator | 10/10 | Harvest corn | | |
| | 10/10 | Harvest corn | | | | |

Table 4. Calibrated CN2 and esco parameters determined for each plot

| Plot No. | Crop-Tillage | CN2 | esco |
|---|---|---|---|
| 21 | CC-CP | 64 | 0.76 |
| 26 | CC-CP | 67 | 0.81 |
| 15 | SC-NT | 69 | 0.85 |
| 29 | SC-NT | 71 | 0.91 |
| 24 | CS-NT | 65 | 0.89 |
| 28 | CS-NT | 68 | 0.82 |

Table 5. Statistical results comparing measured and simulated values for each plot for calibartion period (1995)[a]

| Plot No. | Crop-Tillage | $r^2$ | E | $D_v$ |
|---|---|---|---|---|
| 21 | CC-CP | 0.84 | 0.52 | -7.88 |
| 26 | CC-CP | 0.97 | 0.63 | -7.56 |
| 15 | SC-NT | 0.73 | 0.58 | -7.56 |
| 29 | SC-NT | 0.91 | 0.68 | 5.95 |
| 24 | CS-NT | 0.70 | 0.61 | -8.37 |
| 28 | CS-NT | 0.80 | 0.54 | -8.10 |

[a]$r^2$ = Coefficient of determination; E = Nash-Surclifee Coefficient;
$D_v$ = Deviation of tile volume

Table 6. Standard errors computed for the regression intercepts and slopes for the 1995 calibration year

| Plot No. | Intercept | | Slope | |
|---|---|---|---|---|
| | Estimated | SE[a] | Estimated | SE |
| 21 | 8.85 | 1.35 | 0.33 | 0.05 |
| 26 | 8.04 | 0.72 | 0.4 | 0.03 |
| 15 | 6.33 | 1.96 | 0.4 | 0.09 |
| 29 | 8.12 | 1.25 | 0.45 | 0.05 |
| 24 | 6.59 | 2.54 | 0.45 | 0.11 |
| 28 | 4.29 | 0.8 | 0.34 | 0.07 |

[a]SE = Standard error

Table 7. Cumulative observed and predicted annual tile flow for 1993-1997[a]

| Plot No. | 1993 Obs. (mm) | 1993 Pred. (mm) | 1993 $D_v$ (%) | 1994 Obs. (mm) | 1994 Pred. (mm) | 1994 $D_v$ (%) | 1995 Obs. (mm) | 1995 Pred. (mm) | 1995 $D_v$ (%) | 1996 Obs. (mm) | 1996 Pred. (mm) | 1996 $D_v$ (%) | 1997 Obs. (mm) | 1997 Pred. (mm) | 1997 $D_v$ (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 21 | 406.93 | 354.90 | -12.79 | 87.53 | 98.60 | 12.65 | 133.95 | 123.40 | -7.88 | 73.86 | 64.22 | -13.05 | 94.99 | 102.33 | 7.73 |
| 26 | 463.29 | 417.10 | -9.97 | 67.65 | 75.10 | 11.01 | 137.17 | 126.80 | -7.56 | 56.55 | 73.31 | 29.64 | 86.62 | 94.80 | 9.44 |
| 15 | 390.36 | 430.16 | 10.20 | 43.56 | 51.48 | 18.18 | 108.20 | 100.02 | -7.56 | 48.15 | 58.36 | 21.20 | 71.26 | 76.90 | 7.91 |
| 29 | 436.65 | 386.68 | -11.44 | 82.80 | 89.46 | 8.04 | 119.96 | 127.10 | 5.95 | 60.08 | 69.02 | 14.88 | 67.05 | 72.22 | 7.71 |
| 24 | 318.68 | 288.35 | -9.52 | 69.24 | 74.80 | 8.03 | 128.62 | 117.86 | -8.37 | 54.82 | 65.25 | 19.03 | 82.86 | 69.27 | -16.40 |
| 28 | 184.57 | 169.00 | -8.44 | 48.75 | 45.86 | -5.93 | 67.14 | 61.70 | -8.10 | 38.73 | 43.60 | 12.57 | 28.70 | 31.40 | 9.41 |

[a]Obs.= Observed, Pred.= Predicted, $D_v$ = Deviation of tile volume

Table 8. Statistical results comparing measured and simulated data for each plot for the four-year validation period (1993,94-1996,97)[a]

| Plot No. | Crop-Tillage | $r^2$ | E | $D_v$ |
|---|---|---|---|---|
| 21 | CC-CP | 0.49 | 0.47 | -6.52 |
| 26 | CC-CP | 0.59 | 0.58 | -2.05 |
| 15 | SC-NT | 0.67 | 0.67 | 11.49 |
| 29 | SC-NT | 0.56 | 0.54 | -3.74 |
| 24 | CS-NT | 0.64 | 0.60 | -4.26 |
| 28 | CS-NT | 0.65 | 0.59 | -3.62 |

[a]$r^2$ = Coefficient of determination; E = Nash-Surclifee Coefficient;
$D_v$ = Deviation of tile volume

Table 9. Standard errors computed for the regression intercepts and slopes for the 1993-94 and 1996-97 validation period

| Plot No. | Intercept | | Slope | |
|---|---|---|---|---|
| | Estimated | SE[a] | Estimated | SE |
| 21 | 10 | 2.38 | 0.39 | 0.07 |
| 26 | 9.02 | 2.57 | 0.5 | 0.07 |
| 15 | 7.1 | 2.49 | 0.65 | 0.08 |
| 29 | 8.78 | 2.64 | 0.47 | 0.07 |
| 24 | 7.1 | 1.61 | 0.47 | 0.06 |
| 28 | 4.25 | 0.96 | 0.46 | 0.06 |

[a]SE = Standard error

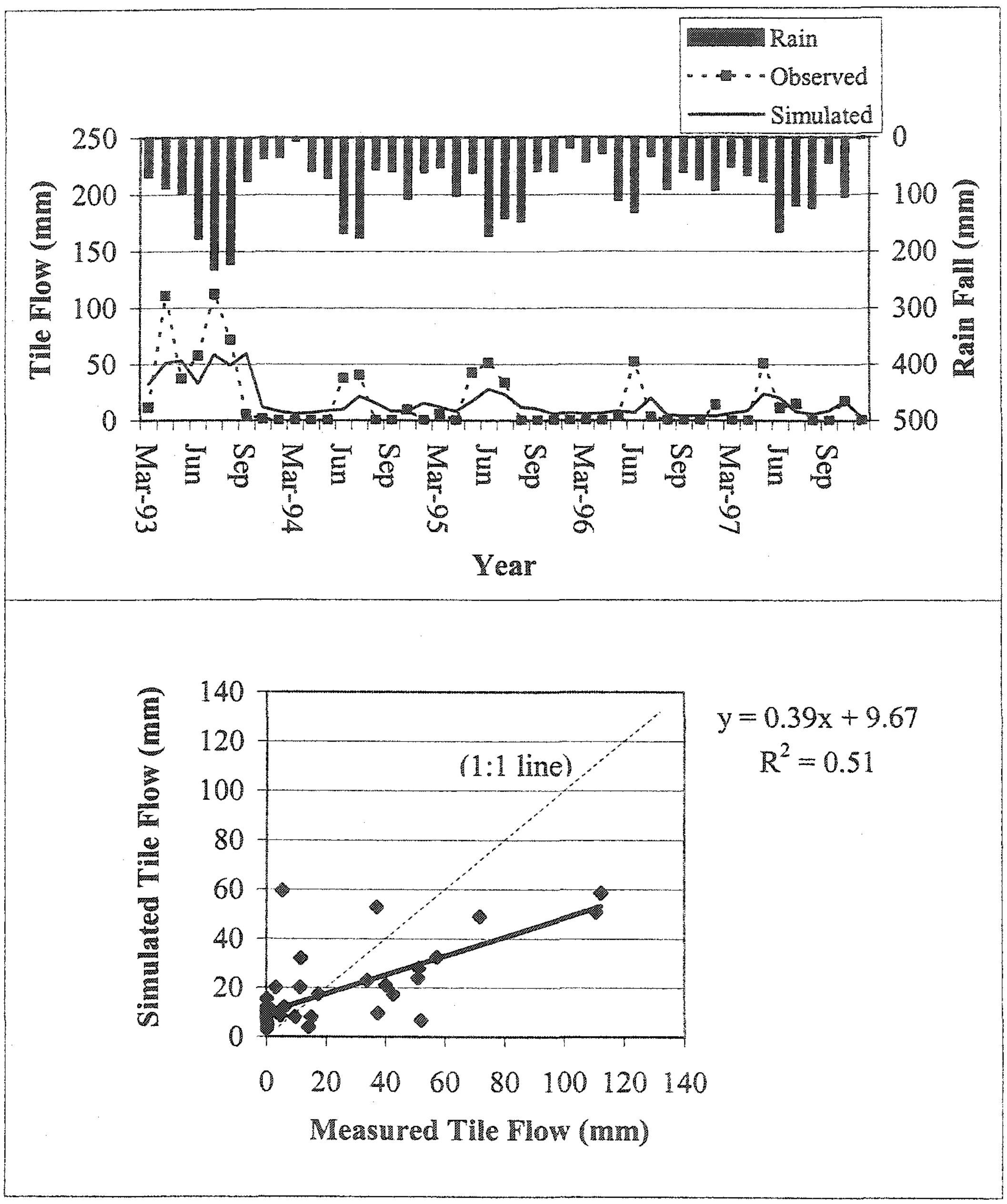


Figure 1. Time series and scattergram comparisons between measured and simulated monthly tile flow (mm) during 1993-97 for plot 21

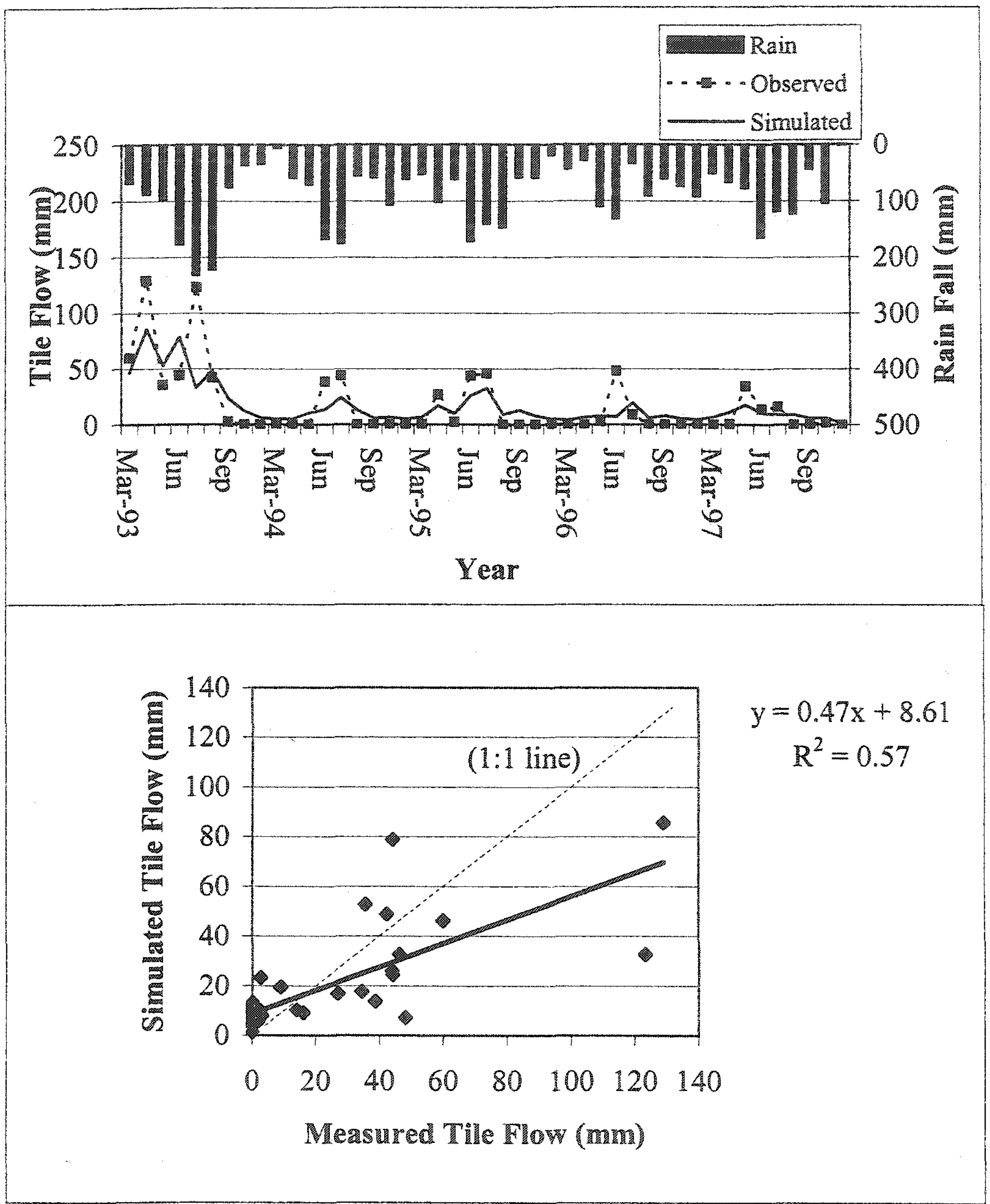


Figure 2. Time series and scattergram comparisons between measured and simulated monthly tile flow (mm) during 1993-97 for plot 29

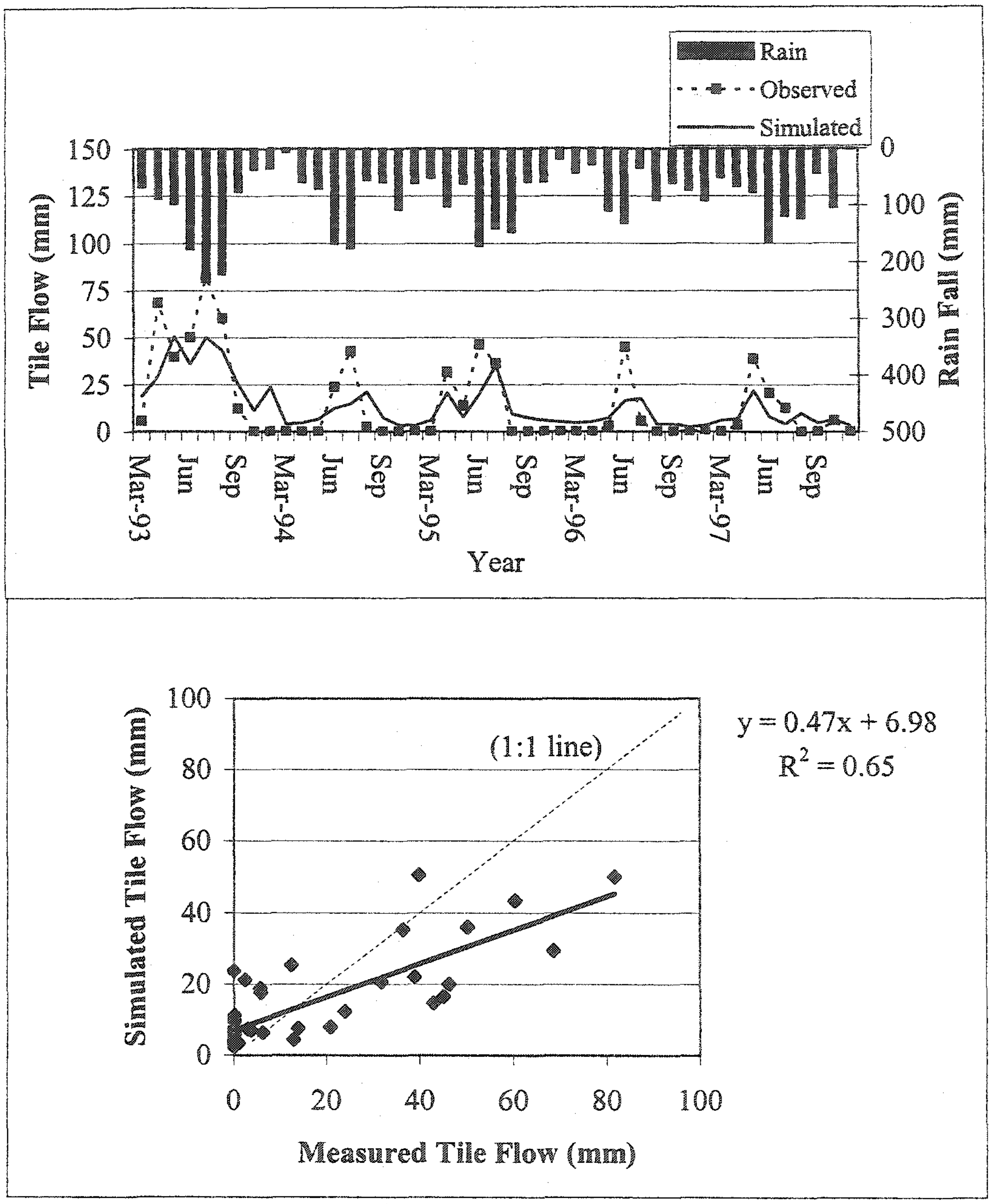


Figure 3. Time series and scattergram comparisons between measured and simulated monthly tile flow (mm) during 1993-97 for plot 24

# CHAPTER 4. EVALUATION OF SWAT MODEL FOR THREE MANAGEMENT SYSTEMS FOR IOWA SOILS

## Part II: Nitrate Losses with Tile Flow

A paper to be submitted to Transaction of the ASAE

K. Ahmad, P. W. Gassman, and R. S. Kanwar[1]

**Abstract**

Calibration and evaluation of water quality models is important before these models can be applied for watershed and assessment for a wide range of for a management, soil, and climate conditions. In this study, the Soil and Water Assessment Tool (SWAT) model was calibrated and validated using five years of nitrate ($NO_3$-N) loss data collected from field research plots near Nashua, Iowa for three different combinations of tillage and cropping systems: continuous corn - chisel plow, corn-soybean - no-till, and soybean-corn - no-till. Each system was analyzed for two research plots that differed in soil type and slope gradient. Calibration of SWAT was performed using tile flow $NO_3$-N loss data measured in 1995 while validation was conducted by comparing the model output with measured $NO_3$-N losses with tile flow observed in 1993-94 and 1996-97. Differences ranging from 2 to 10% were found between annual $NO_3$-N losses during the validation period. Model efficiencies and $r^2$

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values calculated for the same periods ranged from 0.54 to 0.69 and 0.60 to 0.86, respectively, indicating that the model tracked the monthly observations reasonably well. However, the peak $NO_3$-N losses were consistently under-predicted for all three combinations of tillage and cropping systems. Overall, results of this study indicate that SWAT model has the potential to simulate the impact of different management and cropping systems on $NO_3$-N losses with tile flow.

**Keywords:** Calibration, SWAT, nitrate leaching, validation

## Introduction

Nitrogen application to cropland is essential for sustaining fiber and food production. The use of nitrogen and other agrochemicals has increased worldwide within the agricultural sector to meet the demands of an expanding global population and improved living standards. In the U.S., about 53% of the commercial nitrogen fertilizer is used in the north central region; 83% of the U.S. corn crop is grown in this region, which receives the majority of the nitrogen inputs (Power et al., 1998). In addition, significant amounts of nitrogen are also applied in livestock manure to some of the cropland in the region.

The positive benefits of these nitrogen inputs have been offset to some degree by unintended negative externalities. Nitrogen applied in fertilizer and via manure to crop fields has been identified as a key source of nonpoint-source nitrate ($NO_3$-N) pollution of surface and ground water bodies in the region (Jaynes et al., 1999; Kanwar et al., 1999; Rejesus and Hornbaker, 1999). Two factors that contribute to higher $NO_3$-N losses in parts of the north central region are the over application of nitrogen and the use of subsurface drainage tiles.

Over application of nitrogen to continuous corn has been associated with excess residual soil $NO_3$-N at the end of a growing season, which may be more susceptible to leaching over winter when precipitation exceeds evapotranpiration (Katupitiya et al. 1997). Over application of nitrogen to corn following soybean has also proven problematic, due to under-accounting of the nitrogen credit provided by the soybean crop (Lory et al., 1995).

Subsurface tile drains not only remove excess water from the root zone but also transport soluble $NO_3$-N from the bottom of root zone to drainage ditches and streams (Hatfield et al., 1998). In the U.S. Corn Belt, higher $NO_3$-N concentrations in the soil profile have resulted due to continuous corn production relative to corn grown in rotation with soybean (Anderson et al., 1997; Kanwar et al., 1997). Randall (1998) reports that elevated $NO_3$-N concentrations in the Mississippi River are due in part to the extensive amount of tile drainage used in portions of the Upper Mississippi River Basin.

Numerous field studies have been conducted to assess the impacts of different management and cropping systems on $NO_3$-N losses to tile drains (e.g., Kanwar and Baker, 1991; Kanwar et al., 1997; Kanwar et al., 1998; Kanwar et al., 1999; Randall et al., 1997; Randall 1998). These experiments have provided critical insights into the processes that dominant $NO_3$-N losses to tile drains, and have provided important guidance on solutions to the problem. However, it is not possible to assess every possible combination of management and cropping system, climate, soil properties, and landscape features with field experiments.

Computer simulation models offer efficient and cost-effective alternatives to field experiments for evaluating the impact of different farming practices on soil and water quality (Knisel and Turtola, 2000). The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) is a conceptual, physically-based long-term continuous watershed scale simulation model that is capable of simulating a high level of spatial detail by allowing the division of a watershed into a large number of subwatersheds. In SWAT, a watershed is divided into multiple subwatersheds, which are then further subdivided into unique soil/landuse characteristics called Hydrologic Response Units (HRUs). Flow generation, sediment yield, and non-point-source loadings are summed across all HRUs in a subwatershed, and the resulting loads are then routed through channels, ponds, and/or reservoirs to the watershed outlet. The model integrates functionalities of several other models, allowing for the simulation of climate, hydrology, plant growth, erosion, nutrient transport and transformation, pesticide transport and management practices. Previous applications of SWAT have compared favorably with measured data for a variety of watershed scales (Srinivasan and Arnold, 1994; Rosenthal et al., 1995; Arnold and Allen, 1996; Srinivasan et al.,1998; Arnold et al., 1999; Saleh et al., 2000).

The overall goal of this research was to test the ability of SWAT (version 99.2) model for predicting $NO_3$-N concentrations with tile flow, by comparing the model output versus measured data collected at field sites located near Nashua in northeast Iowa. The specific objectives were:

1. to calibrate the SWAT model by using measured data on $NO_3$-N losses with tile water measured in 1995 for three different combinations of tillage and cropping systems, and
2. to validate the calibrated SWAT model by comparing the predicted versus measured $NO_3$-N losses with tile water for the three systems during 1993-94 and 1996-97.

**Model Description**

The three major components of SWAT model are subbasin, reservoir routing, and channel routing. There are eight major divisions of the subbasin component: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, agricultural management, and pesticides. The hydrology component is comprised of surface runoff, percolation, lateral subsurface flow, groundwater flow, snowmelt, evapotranspiration (ET), transmission losses, and ponds. The soil profile can be divided into multiple layers. Soil water processes include infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers. Further details on the hydrology and other components are described in Arnold et al. (1998) and Neitsch et al. (2001). Specific descriptions regarding tile drain and other hydrologically relevant inputs and assumptions that underpin this study are given in Ahmad et al. (2003). Further description of the SWAT nitrogen submodel is provided in the following paragraph:

**SWAT Nitrogen Submodel**

The transformation and movement of nitrogen within an HRU is simulated in SWAT as a function of a nitrogen cycle that consists of several pools. SWAT tracks five different nitrogen pools in the soil, two of which are inorganic (mineral) forms while the other three consist of organic forms. Inorganic and organic forms of nitrogen are input into the soil system via commercial fertilizer and/or livestock manure; organic nitrogen is also input from plant residue.

Losses of nitrogen from the soil profile in SWAT occur by crop uptake, in surface runoff via both the solution phase and on eroded sediment, in percolation below the root zone, in lateral subsurface flow (including tile drains), and by volatilization to the atmosphere. A supply-and-demand approach is used to simulate crop uptake of nitrogen. Movement of nitrate ($NO_3$-N) in surface runoff, lateral subsurface flow, and percolation is computed as the product of the average soil layer $NO_3$-N concentration and the volume of water in each flow pathway. Movement of organic nitrogen on eroded sediment is estimated with a loading function initially derived by McElroy et al. (1976) and later modified for individual runoff events by Williams and Hann (1978). Daily losses are computed with the loading function as a function of the nitrogen concentration in the topsoil layer, the sediment yield, and an enrichment ratio.]

**Movement of $NO_3$-N to Tile Drains**

The amount of nitrate transported by the tile flow is estimated as follows

$$V_{NO_3} = q_{tile} \times C_{NO_3} \qquad (1)$$

Where $V_{NO3}$ is the amount transported by the tile flow and $C_{NO3}$ is the concentration of nitrate in the tile flow for a given layer (kg N/mm $H_2O$), and is given by

$$C_{NO_3} = \frac{NO_{3_{ly}}.\exp\left[\frac{-q_{tile}}{(1-\theta_e).SAT_{ly}}\right]}{q_{tile}} \qquad (2)$$

where $NO_{3ly}$ is the amount of nitrate in the layer (kg N/ha), $\theta_e$ is the fraction of porosity from which anions are excluded, and $SAT_{ly}$ is the saturated water content of the soil layer (mm $H_2O$) and $q_{tile}$ is the amount of water removed from the layer on a given day by tile drainage (mm $H_2O$) and is calculated by

$$q_{tile} = (SW_{ly} - FC_{ly})(1 - e^{(\frac{-24}{t_{drain}})}) \quad \text{if} \quad SW_{ly} > FC_{ly} \qquad (3)$$

Where SW is soil water (mm $H_2O$) content of the layer on a given day, and $t_{drain}$ is time required to drain the soil to field capacity (hrs). Water entering the tiles is treated like lateral flow.

Users may define the amount of nitrate and organic nitrogen contained in humic substances for all soil layers at the beginning of the simulation. If the user does not specify initial nitrogen concentrations, SWAT will initialize levels of nitrogen in the different pools. Initial nitrate levels in the soil are varied by depth using the relationship:

$$NO_{3_{conc,z}} = 7.\exp\left(\frac{-z}{1000}\right) \qquad (4)$$

where $NO_{3conc,z}$ is the concentration of nitrate in the soil at depth $z$ (mg/kg or ppm), and $z$ is the depth from the soil surface (mm).

**Site Description**

The measured $NO_3$-N loss data with tile water was collected from six field plots during 1993-97 at Iowa State University's Northeast Research Center (NERC) near Nashua.

The soils at this site are Floyd loam (fine-loamy, mixed, mesic Aquic Hapludolls), Readlyn loam (fine-loamy, mixed, mesic Aquic Hapludolls), and Kenyon silty-clay loam (fine-loamy, mixed, mesic, Typic Hapludolls). These silty soils are moderately well to poorly drained, lie over loamy glacial till (USDA-SCS, 1977), have 3 to 4% organic matter, and belong to the Kenyon-Clyde-Floyd soil association. These soils have seasonally water table that vary from 0.60 to 1.52 meter below the surface, and thus benefit form subsurface drainage. All three soils are classified as being hydrologic group B.

The site has 36, .4-hectore plots that were managed with consistent tillage and cropping practices for the duration of the study period. Subsurface drainage tiles were installed about 1.2 meters deep at a 28.5 m spacing in 1979. Each plot has a tile line along the center and along the north-south borders. The plots are isolated on the east and west side by 9.15 m grass strips. Center drains were routed to sums for monitoring subsurface drain flows, while border drains isolated plots on the north and south side. Three treatments of tillage and crop rotation combinations were evaluated in this study for six different plots (Table 1), and are defined as follows:

Treatment 1: Continuous corn with spring chisel plow (CC-CP).

Treatment2: No-till soybean-corn rotation (soybean planted in 1993) (SC-NT).

Treatment3: No-till corn-soybean rotation (corn planted in 1993) (CS-NT).

## Model Input Data

### Climate

Daily values of precipitation, maximum and minimum air temperature, wind speed, solar radiation, and relative humidity are required for SWAT. If measured daily precipitation and maximum/minimum air temperatures are available, they can be input directly to SWAT. If not, they can be generated within SWAT with a weather generator. For this study, precipitation and temperature data measured at the Nashua site were input for the entire five-year period. Daily solar radiation, wind speed, and relative humidity are always generated in SWAT 99.2; monthly weather statistics for Osage, Iowa, located approximately 50 km from the study site, were used to generate these inputs for this study.

### Soil Properties

The model requires the division of the soil profile into specific layers. The Kenyon, Readlyn, and Floyd profiles were divided into six layers based on the layers reported for those soils by Singh et al. (1996). Physical properties such as bulk density, available water capacity, saturated hydraulic conductivity, initial $NO_3$ concentration, and particle-size distribution were input for each layer. Soil layer data reported by Singh et al. (1996) were used for this study. Data on selected properties for the three soils are listed in Table 2 as a function of depth.

**Land Management**

Relevant data depicting planting, harvest, irrigation, nutrient and pesticide applications, and tillage operations is required to simulate specific management systems in SWAT model. The management systems simulated for each treatment are given in Table 3. A yearly nitrogen application of 135 kg/ha was applied for the CC-CP management system. Variable rates of nitrogen were applied to corn for the other two systems, ranging from 125 to 193 kg/ha for CS-NT and between 169 and 195 kg/ha for the SC-NT system. Smaller nitrogen applications of 28 kg/ha were also applied in the form of starter fertilizer to corn at planting. No nitrogen applications were applied to soybean in either CS-NT or SC-NT management systems.

**Calibration Procedure**

The initial calibration of SWAT model for the six plots focused on the tile flow predictions as reported by Ahmad et al. (2003). The tile flow calibrations were performed for each individual plot by adjusting the condition II runoff curve numbers (CN2) and soil evaporation coefficient (esco) for the 1995 growing season period, until the best match was achieved between the predicted and measured values. Further calibration was then performed in this study for each plot to obtain the best match between the predicted and observed $NO_3$-N loss with tile water for the 1995 growing season.

The criterion used for calibrating the model in this study was to minimize the difference between the measured and simulated annual $NO_3$-N loss and to match the simulated monthly $NO_3$-N losses with the corresponding observed values. A trial and error procedure was used to determine the best value of the nitrogen percolation coefficient (nperco), which controls the amount of mineral nitrogen removed from the top 10.0 mm surface layer in surface runoff relative to the amount removed via percolation. The value of nperco can range from 0.0 to 1.0. When nperco is 0.0, the concentration of mineral N in the surface runoff is zero. When nperco is 1.0, the surface runoff has the same concentration of mineral nitrogen as the percolate. If no value for nperco is entered, the model will set nperco equal to 0.20. During the calibration procedure, the nperco value was allowed to vary between 0.22 and 0.69 for the six different plots. The procedure was continued until the shapes of the simulated monthly $NO_3$-N loss trends were in reasonable agreement with the observed monthly time series, and the predicted total annual $NO_3$-N losses were within 15% of the observed total annual $NO_3$-N losses.

To test the ability of the model to predict system response, the model was evaluated with measured $NO_3$-N loss with tile flow data for 1993-94 and 1996-97 for all tillage systems again on plot-by-plot basis. A final calibration step involved adjusting the initial $NO_3$-N concentrations in the soil profile to ensure that the simulated $NO_3$-N loss with tile flow started at approximately the same time as the observed $NO_3$-N loss.

## Model Evaluation Criteria

To validate the model, the simulated nitrate losses were compared with the corresponding observed $NO_3$-N losses with tile flow water on a plot-by-plot basis for both 1993-94 and 1996-97 for all three tillage-cropping systems. The validation runs were performed for the complete five-year period that included 1995, as opposed to executing the model for two separate time periods. The statistical criteria that were used by Ahmad et al. (2003) to judge the model's prediction capability were again used in this study, which included the coefficient of determination ($r^2$), Nash-Sutcliffe model efficiency (E), and the deviation of the tile flow volume ($D_v$). The $r^2$ and E statistics were used to evaluate the monthly $NO_3$-N loss results while the $D_v$ was used to assess the accuracy of the predicted annual and annual average $NO_3$-N losses. The $r^2$ represents the percentage of the variance in the measured data that is explained by the simulated data and varies between 0 and 1, with a value of 1 indicating a perfect fit. The E statistic indicates how close the plot of the simulated versus observed values come to the 1:1 line (Nash and Sutcliffe, 1970). Further details on these statistics are provided in Ahmad et al. (2003).

**Results and Discussion**

According to Duffy et al. (1975), predicted $NO_3$-N losses with tile flow are sensitive to the hydrologic component of a model; therefore, the various processes of water movement in the soil profile are key factors that ultimately influence the predicted $NO_3$-N losses. The loss of $NO_3$-N via tile flow at Nashua is driven by precipitation inputs because there is no other source of water entering the soil profile. The first year of study, 1993, was an extremely wet year with a total annual rainfall of about 1026.32 mm, which was significantly greater than the annual average rainfall of about 800 mm at the site. The years 1994, 1996, and 1997 had less rainfall than the normal whereas 1995 was closer to normal. These precipitation patterns clearly impacted the observed and simulated results.

Table 4 shows the cumulative observed and predicted annual $NO_3$-N losses (kg/ha) with tile flow and corresponding $D_v$ values for all five years. The predicted annual $NO_3$-N losses with tile flow for the calibration year (1995) accurately reflected the observed values, as indicated by the relatively low $D_v$ values that range from -7.3 to 5.5. The predicted annual

$NO_3$-N losses with tile water for the four validation years were not close to the observed values, especially for 1994 and 1997, as reflected by $D_v$ values that ranged from about 7.2 to 20.4

Flow weighted average $NO_3$-N concentrations provide an alternative way of presenting the impacts of the three treatments, which have been reported to be a better indicator for evaluating the chemical loads (Anderson et al., 1997). The concentrations are computed by dividing the given $NO_3$-N loss by the respective flow. Any error in the predicted $NO_3$-N losses with tile water can be further compounded for the concentration computations, because a low value of tile flow (denominator) can result in a high concentration value. The predicted concentrations were always within 12% of the observed values for all of the treatment-plot combinations in both the calibration and validation periods, except for plots 15 and 28 (Table 5). The model over-predicted the concentrations in 1995 and 1997, and under-predicted them in 1993 and 1996.

The $NO_3$-N losses for the CP-CC system (plots 21 and 26) were generally greater than those predicted (and measured) for the other two management systems (Table 4). Similar findings have been reported when application of N from fertilizer to continuous corn caused build up of excess soil nitrate at the end of the growing season (Lory et al., 1995). The amount of $NO_3$-N loss via tile flow for soybeans plots was lower which were rotated with corn. These plots were under corn in the preceding year, which shows that corn leaves greater amount of residual nitrate in the root zone compared with that of soybean when grown in the preceding year. Soybean is an excellent scavenger for nitrogen compared with corn and can reduce the amount of nitrates in the soil after harvest (Power et al., 1998). Though amount of residual nitrate is affected by many other factors such as nitrification/denitrification, mineralization/immobilization and leaching, which is heavily depend on the amount of precipitation compared with that of evapotranpiration. The process of nitrification/denitrification are controlled by soil temperature and soil moisture, which can be affected by shading due to different levels of canopy cover and soil moisture removal by corn and soybeans crops (Staver and Brinsfiled, 1995).

The $r^2$ and E statistics were computed based on the monthly $NO_3$-N loss (kg/ha) estimates for both the calibration and validation periods (Tables 6 and 7). The $r^2$ values determined for the calibration year ranged from 0.70 to 0.92 (Table 6), indicating a strong correlation between the predicted and the measure $NO_3$-N tile flow losses. The E values also indicate that the model captured much of the observed $NO_3$-N trends (Table 6). The $r^2$ and E values for the validation period (Table 7) ranged from 0.60 to 0.86 and 0.54 to 0.69, respectively. These results indicate that the correlation between the predicted and observed values were not as accurate for the four-year validation period as compared to the calibration year. However, the validation period $r^2$ and E values show that SWAT was able to track much of the measured $NO_3$-N loss trends over the four years that were simulated. A comparison of the four-year annual average $D_v$ values for the validation period (Table 7) versus the calibration year $D_v$ values (Table 6) shows that the long-term average annual losses estimated for the validation years were actually closer to the corresponding measured values, relative to the 1995 calibration year (except for the plot 24 simulations).

Figures 1 to 3 show the time series plots of the monthly observed and simulated $NO_3$-N losses (kg/ha) via tile flow. The figures indicate that SWAT generally tracked the measured $NO_3$-N loss trends, with the predicted peak $NO_3$-N loss months usually occurring at the same time that they were actually observed in the field. However, the months in which peak $NO_3$-N losses occurred were usually under-predicted by a factor of two. The model also tended to predict some $NO_3$-N losses in months that were observed to have no $NO_3$-N losses. There was a net decrease in both the predicted and measured $NO_3$-N losses with tile flow after winter because immobilization and denitrification, which take place only in the upper microbial active zone, were limited by the relatively cold soil temperatures during the winter months. Some losses, particularly denitrification, may have occurred in early spring when the soil temperature and moisture levels were higher (Jekola and Randall, 1989). The scattergrams in Figure 4 show the predicted versus measured monthly flows relative to a 1:1 line for the full five-year period. Some of the points deviated considerably from the 1:1 line. Several of the simulated values are also shown on the y-axis in each scattergram, underscoring again the fact that the model predicted small amounts of $NO_3$-N losses with tile flow during periods in which no $NO_3$-N losses with tile flow occurred.

Standard errors were also computed for the slope and intercept components of the regressions (Table 8 and 9). T-tests performed using these standard errors indicated that the slopes and intercepts determined for the simulated flows for each plot were all significantly different from a slope of 1 and an intercept of zero, respectively. The t-test results reveal that the simulated values differed significantly from the 1:1 line, and suggest that the predicted values were weaker than what the $R^2$ values indicate.

Discrepancies between the predicted and observed $NO_3$-N losses with tile flow could be due to several reasons. Ahmad et al. (2003) suggest that inaccuracies that occurred for the tile flow predictions could have been due in part to the inability of SWAT to capture the effects of macropore flow. This weakness along with other inaccuracies in the hydrologic calculations will in turn introduce errors into the estimates of the tile flow $NO_3$-N losses. The model was also unable to capture the variability in soil spatial properties that exist in these six different plots. Overall, the model predictions were encouraging, given the fact that a high degree of spatial variability exists for the actual field conditions.

## Summary and Conclusions

In this study, the Soil and Water Assessment Tool (SWAT) model was tested and validated using five years of nitrate ($NO_3$-N) loss data collected from field research plots near Nashua, Iowa for three different combinations of tillage and cropping systems: continuous corn - chisel plow, corn-soybean - no-till, and soybean-corn - no-till. Each system was analyzed for two research plots that differed in soil type and slope gradient. Calibration of SWAT model was performed with measured $NO_3$-N loss data with tile flow water for 1995 while validation was conducted by comparing the model output with measured $NO_3$-N losses observed in 1993-94 and 1996-97.

A comparison between the predicted annual $NO_3$-N losses with tile flow for the calibration year (1995) and the corresponding observed values resulted in relatively low $D_v$ values that ranged from -7.34 to 5.50. These $D_v$ values indicate that the model simulated close to the measured values for the total $NO_3$-N losses for 1995. The predicted annual $NO_3$-N losses with tile flow for the four validation years were not close to the measured values, especially for 1994 and 1997, as reflected by $D_v$ values that ranged from about 7.2 to 20.4. However, the $D_v$ values calculated for the long-term average annual $NO_3$-N losses estimated for the validation years were actually closer to the corresponding measured values, relative to the 1995 calibration year (except for plot 24 simulations), indicating that predicted $NO_3$-N losses for the validation years were more close to that of predicted values for the 1995 calibration year.

The $r^2$ values determined for the calibration year ranged from 0.70 to 0.92, indicating a strong correlation between the predicted and the measure $NO_3$-N losses with tile flow. The E values ranged from 0.56 to 0.82, indicating that the model captured much of the observed $NO_3$-N loss trends. The $r^2$ and E values for the validation period ranged from 0.60 to 0.86 and 0.54 to 0.69, respectively. These results indicate that the correlation between the predicted and observed values for $NO_3$-N losses were not as good for the four-year validation period as compared to the calibration year. However, the validation period $r^2$ and E values show that SWAT was able to track much of the measured $NO_3$-N loss trends over the four years of simulation period.

Despite the fact that the $r^2$ and E statistics were relatively strong, the results revealed that the model was unable to predict the magnitude of the monthly peak tile flows in each of the five simulated years. The model also predicted low levels of $NO_3$-N losses with tile flow during periods in which no $NO_3$-N loss with tile flow was observed. These discrepancies between the predicted and observed $NO_3$-N losses with tile flow are in part due to complexities introduced by SWAT's hydrologic computations. These errors were further compounded by weaknesses in the model in capturing the complete nitrogen cycle that occurs in soils cropped with row crops such as cron and soybean.

The overall evaluation of the SWAT model indicates that model has the capability of predicting $NO_3$-N losses with tile flows satisfactory for different soil types, slopes, and management systems. However, these results also point to significant weaknesses in SWAT 99.2's ability to track all components of nitrogen movement to tile flow in crop fields.

Further research work is needed, with more current versions of SWAT, to improve the accuracy of the results reported here. Significant efforts have been initiated to improve the tile flow and corresponding $NO_3$-N loss predictions in more recent releases of SWAT (Arnold, J.G. Personal communication. Grassland, Soil, and Water Research Lab., USDA-ARS, Temple, TX).

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Table1 . Soil type and mangement practice for plots

| Plot No. | Mnagement Pracitce | Soil Type |
|---|---|---|
| 21 (3.2%)[a] | CP,CC | Readlyn |
| 26 (4.4%) | CP,CC | Floyd |
| | | |
| 24 (1.6%) | NT,CS | Kenyon |
| 28 (3.6%) | NT,CS | Kenyon |
| | | |
| 15 (1.1%) | NT,SC | Readlyn |
| 29 (3.2%) | NT,SC | Kenyon |

[a]Slope

CP,CC: chisel plow, continues corn; NT, CS: notill, corn soybean; NT, SC: no till, soybean corn

Table 2 . Dates of tillage, planting, chemical application, and harvesting for simulation

| Year | CC-CP | | CS-NT | | SC-NT | |
|---|---|---|---|---|---|---|
| | **Date** | **Operation** | **Date** | **Operation** | **Date** | **Operation** |
| 1993 | 5/14 | Elem-N (135 Kg/ha) | 5/17 | Elem-N (28 Kg/ha) | 5/26 | Plant soybean |
| | 5/3 | Chisel plow | 5/17 | Plant corn | 10/7 | Harvest soybaen |
| | 5/17 | Plant corn | 7/21 | Elem-N (144 kg/ha) | | |
| | 7/21 | Row Cultivator | 10/21 | Harvest corn | | |
| | 10/25 | Harvest corn | | | | |
| 1994 | 5/1 | Chisel plow | 10/6 | Harvest soybaen | 5/2 | Plant corn |
| | 4/24 | Elem-N (135 Kg/ha) | 5/17 | Plant soybean | 5/2 | Elem-N (28 Kg/ha) |
| | 6/2 | Row Cultivator | | | 10/25 | Harvest corn |
| | 9/28 | Harvest corn | | | | |
| 1995 | 5/12 | Elem-N (135 Kg/ha) | 5/16 | Elem-N (28 Kg/ha) | 5/12 | Plant soybean |
| | 5/15 | Chisel plow | 5/16 | Plant corn | 10/11 | Harvest soybaen |
| | 5/16 | Plant corn | 6/22 | Elem-N (193 kg/ha) | | |
| | 6/14 | Row Cultivator | 10/22 | Harvest corn | | |
| | 9/22 | Harvest corn | | | | |
| 1996 | 5/3 | Elem-N (135 Kg/ha) | 5/30 | Plant soybean | 5/21 | Elem-N (28 Kg/ha) |
| | 5/20 | Chisel plow | 10/8 | Harvest soybaen | 5/21 | Plant corn |
| | 5/21 | Plant corn | | | 6/24 | Elem-N (195 kg/ha) |
| | 6/24 | Row Cultivator | | | 10/21 | Harvest corn |
| | 10/21 | Harvest corn | | | | |
| 1997 | 5/12 | Elem-N (135 Kg/ha) | 5/12 | Elem-N (28 Kg/ha) | 5/16 | Plant soybean |
| | 5/12 | Chisel plow | 5/12 | Plant corn | 10/10 | Harvest soybaen |
| | 5/12 | Plant corn | 6/19 | Elem-N (125 kg/ha) | | |
| | 6/19 | Row Cultivator | 10/10 | Harvest corn | | |
| | 10/10 | Harvest corn | | | | |

Table3 . Selected soil properties for different soil horizons used as input for simulations

| Horizon No. | Depth mm | Particle size distribution, % Clay | Silt | Sand | Hydraulic Conductivity mm/hr | Bulk Density $Mg/m^3$ | Organic Carbon % |
|---|---|---|---|---|---|---|---|
| Floyd Soil | | | | | | | |
| 1 | 0-20 | 27 | 44 | 30 | 23.50 | 1.29 | 2.90 |
| 2 | 20-400 | 26 | 42 | 33 | 20.65 | 1.40 | 1.00 |
| 3 | 400-500 | 24 | 22 | 54 | 19.71 | 1.45 | 0.90 |
| 4 | 500-800 | 25 | 29 | 47 | 15.69 | 1.45 | 0.30 |
| 5 | 800-1200 | 24 | 40 | 35 | 13.14 | 1.58 | 0.20 |
| 6 | 1200-1500 | 24 | 40 | 35 | 10.95 | 1.70 | 0.20 |
| Kenyon Soil | | | | | | | |
| 1 | 0-20 | 22 | 42 | 38 | 20.91 | 1.36 | 2.00 |
| 2 | 20-400 | 25 | 34 | 41 | 20.17 | 1.53 | 2.00 |
| 3 | 400-500 | 24 | 32 | 42 | 19.71 | 1.55 | 0.90 |
| 4 | 500-800 | 29 | 28 | 44 | 17.26 | 1.65 | 0.60 |
| 5 | 800-1200 | 25 | 25 | 44 | 13.45 | 1.70 | 0.40 |
| 6 | 1200-1500 | 25 | 25 | 44 | 10.95 | 1.75 | 0.20 |
| Readlyn Soil | | | | | | | |
| 1 | 0-20 | 26 | 43 | 31 | 22.95 | 1.34 | 2.40 |
| 2 | 20-400 | 25 | 43 | 31 | 20.17 | 1.45 | 2.40 |
| 3 | 400-500 | 25 | 38 | 37 | 20.17 | 1.45 | 0.90 |
| 4 | 500-800 | 21 | 24 | 55 | 14.30 | 1.50 | 0.80 |
| 5 | 800-1200 | 25 | 28 | 46 | 13.45 | 1.65 | 0.30 |
| 6 | 1200-1500 | 24 | 28 | 46 | 10.95 | 1.70 | 0.30 |

Table 4. Observed and predicted $NO_3$-N (kg/ha) for 1993-1997

| Plot No. | 1993 | | | 1994 | | | 1995 | | | 1996 | | | 1997 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Obs. kg/ha** | **Pred. kg/ha** | **%D** | **Obs. kg/ha** | **Pred. kg/ha** | **%D** | **Obs. kg/ha** | **Pred. kg/ha** | **%D** | **Obs. kg/ha** | **Pred. kg/ha** | **%D** | **Obs. kg/ha** | **Pred. kg/ha** | **%D** |
| 21 | 49.58 | 42.93 | -13.41 | 9.41 | 10.97 | 16.58 | 17.04 | 15.79 | -7.34 | 9.52 | 8.60 | -9.66 | 6.56 | 7.90 | 20.43 |
| 26 | 47.75 | 42.25 | -11.52 | 6.76 | 7.37 | 9.02 | 16.53 | 15.64 | -5.38 | 6.63 | 7.85 | 18.40 | 4.65 | 5.17 | 11.18 |
| 24 | 28.75 | 24.13 | -16.07 | 3.05 | 3.33 | 9.18 | 14.07 | 13.17 | -6.40 | 8.18 | 8.99 | 9.90 | 10.09 | 8.48 | -15.96 |
| 28 | 15.91 | 14.36 | -9.74 | 1.82 | 2.07 | 13.74 | 6.68 | 6.86 | 2.69 | 6.74 | 5.81 | -13.80 | 3.56 | 4.08 | 14.61 |
| 15 | 21.61 | 19.87 | -8.05 | 2.20 | 2.64 | 20.00 | 7.01 | 7.49 | 6.85 | 7.20 | 6.65 | -7.64 | 5.95 | 6.38 | 7.23 |
| 29 | 26.97 | 22.64 | -16.05 | 7.08 | 7.59 | 7.20 | 9.82 | 10.36 | 5.50 | 7.50 | 8.15 | 8.67 | 4.16 | 4.82 | 15.87 |

Obs.= Observed, Pred.= Predicted

%D: Percent diffrence between predicted and observed data

Table 5. Flow weigted average nitrate concentration (FWANC) for 1993-1997

| Plot No. | 1993 | | | 1994 | | | 1995 | | | 1996 | | | 1997 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Obs. mg/l | Pred. mg/l | %D | Obs. mg/l | Pred. mg/l | %D | Obs. mg/l | Pred. mg/l | %D | Obs. mg/l | Pred. mg/l | %D | Obs. mg/l | Pred. mg/l | %D |
| 21 | 12.18 | 12.10 | -0.72 | 10.75 | 11.13 | 3.49 | 12.72 | 12.80 | 0.59 | 12.89 | 13.39 | 3.90 | 6.91 | 7.72 | 11.79 |
| 26 | 10.31 | 10.13 | -1.72 | 9.99 | 9.81 | -1.79 | 12.05 | 12.33 | 2.35 | 11.72 | 10.71 | -8.67 | 5.37 | 5.45 | 1.59 |
| 24 | 9.02 | 8.37 | -7.24 | 4.40 | 4.45 | 1.06 | 10.94 | 11.17 | 2.15 | 14.92 | 13.78 | -7.67 | 12.18 | 12.24 | 0.53 |
| 28 | 8.62 | 8.21 | -4.78 | 3.73 | 4.51 | 20.90 | 9.95 | 11.12 | 11.75 | 17.40 | 13.33 | -23.43 | 12.40 | 12.99 | 4.75 |
| 15 | 5.54 | 4.62 | -16.56 | 5.05 | 5.13 | 1.54 | 6.48 | 7.49 | 15.59 | 14.95 | 11.39 | -23.80 | 8.35 | 8.30 | -0.64 |
| 29 | 6.18 | 5.85 | -5.21 | 8.55 | 8.48 | -0.78 | 8.19 | 8.15 | -0.43 | 12.48 | 11.81 | -5.41 | 6.20 | 6.67 | 7.57 |

Obs.= Observed, Pred.= Predicted

%D: Percent diffrence between predicted and observed data

Table 6 . SWAT model performance indicators for each plot for calibartion period (1995)

| Plot No. | Tillage treatment | $R^2$ | EF | %D |
|---|---|---|---|---|
| 21 | CC-CP | 0.90 | 0.73 | -7.36 |
| 26 | CC-CP | 0.70 | 0.56 | -5.34 |
| 24 | CS-NT | 0.92 | 0.82 | -6.23 |
| 28 | CS-NT | 0.88 | 0.78 | 5.77 |
| 15 | SC-NT | 0.87 | 0.73 | 6.74 |
| 29 | SC-NT | 0.91 | 0.78 | 5.49 |

$R^2$ = Coefficient of determination; EF = Model efficiency;
%D = Percentage of diffrence

Table 7 . SWAT model performance indicators for each plot for validation period (1993,94-1996,97)

| Plot No. | Tillage treatment | $R^2$ | EF | %D |
|---|---|---|---|---|
| 21 | CC-CP | 0.63 | 0.58 | -6.23 |
| 26 | CC-CP | 0.64 | 0.60 | -4.79 |
| 24 | CS-NT | 0.72 | 0.65 | -10.30 |
| 28 | CS-NT | 0.62 | 0.54 | -1.78 |
| 15 | SC-NT | 0.60 | 0.55 | -3.86 |
| 29 | SC-NT | 0.86 | 0.69 | -5.48 |

$R^2$ = Coefficient of determination; EF = Model efficiency;
%D = Percentage of diffrence

Table 8. Standard errors computed for the regression intercepts and slopes for the 1995 calibration year

| Plot No. | Intercept | | Slope | |
|---|---|---|---|---|
| | Estimated | SE[a] | Estimated | SE |
| 21 | 0.78 | 0.21 | 0.51 | 0.07 |
| 26 | 1.02 | 0.3 | 0.39 | 0.1 |
| 15 | 0.42 | 0.1 | 0.52 | 0.07 |
| 29 | 0.53 | 0.12 | 0.57 | 0.06 |
| 24 | 0.5 | 0.17 | 0.61 | 0.06 |
| 28 | 0.35 | 0.1 | 0.59 | 0.08 |

[a]SE = Standard error

Table 9. Standard errors computed for the regression intercepts and slopes for the 1993-94 and 1996-97 validation period

| Plot No. | Intercept | | Slope | |
|---|---|---|---|---|
| | Estimated | SE[a] | Estimated | SE |
| 21 | 1.01 | 0.26 | 0.45 | 0.06 |
| 26 | 0.85 | 0.24 | 0.48 | 0.06 |
| 15 | 0.55 | 0.13 | 0.43 | 0.06 |
| 29 | 0.6 | 0.09 | 0.47 | 0.03 |
| 24 | 0.56 | 0.14 | 0.5 | 0.05 |
| 28 | 0.45 | 0.09 | 0.4 | 0.05 |

[a]SE = Standard error

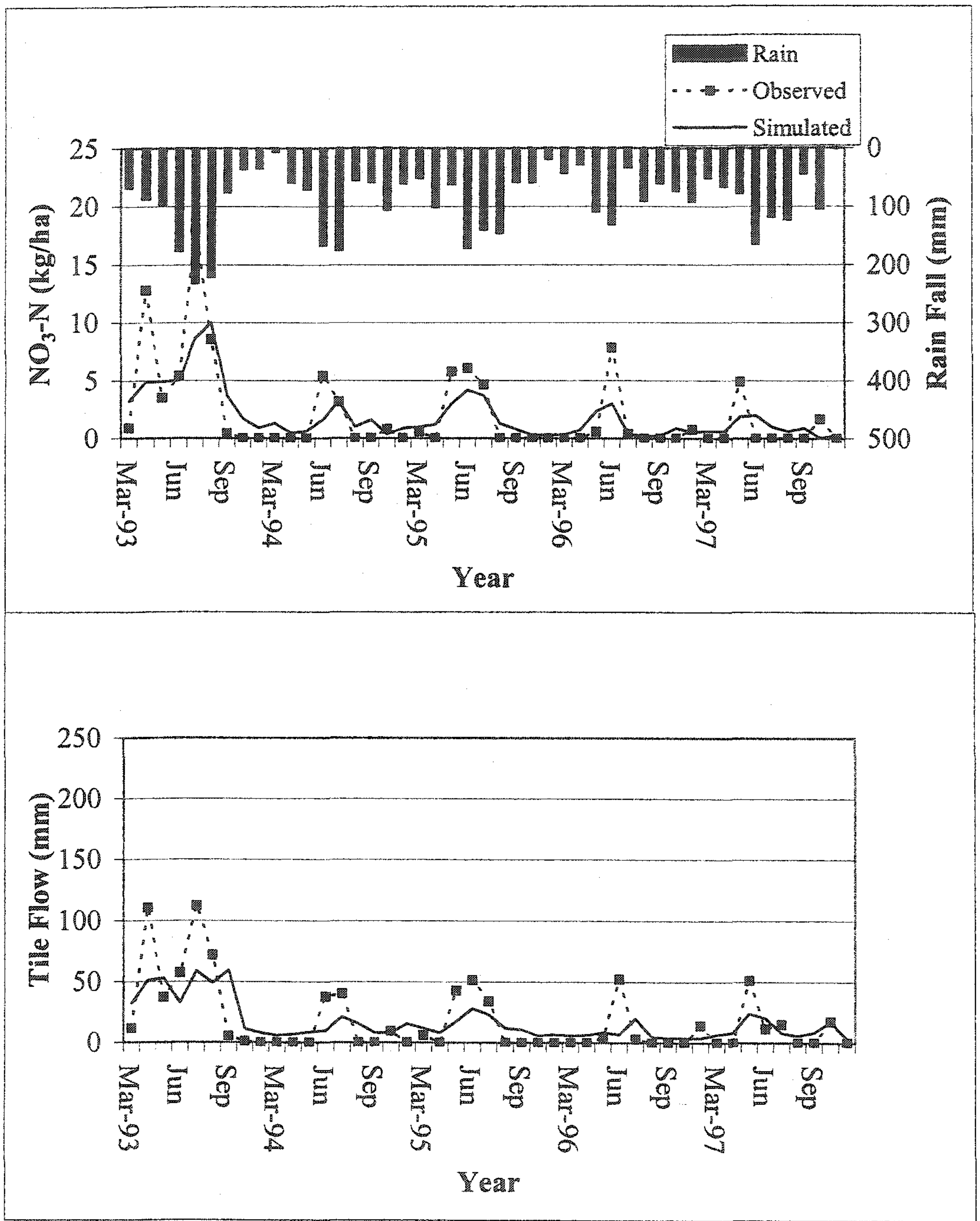



Figure 1. Time series comparisons between measured and simulated monthly for $NO_3$-N losses (kg/ha) with tile flow and for tile flow (mm) during 1993-97 for plot 21

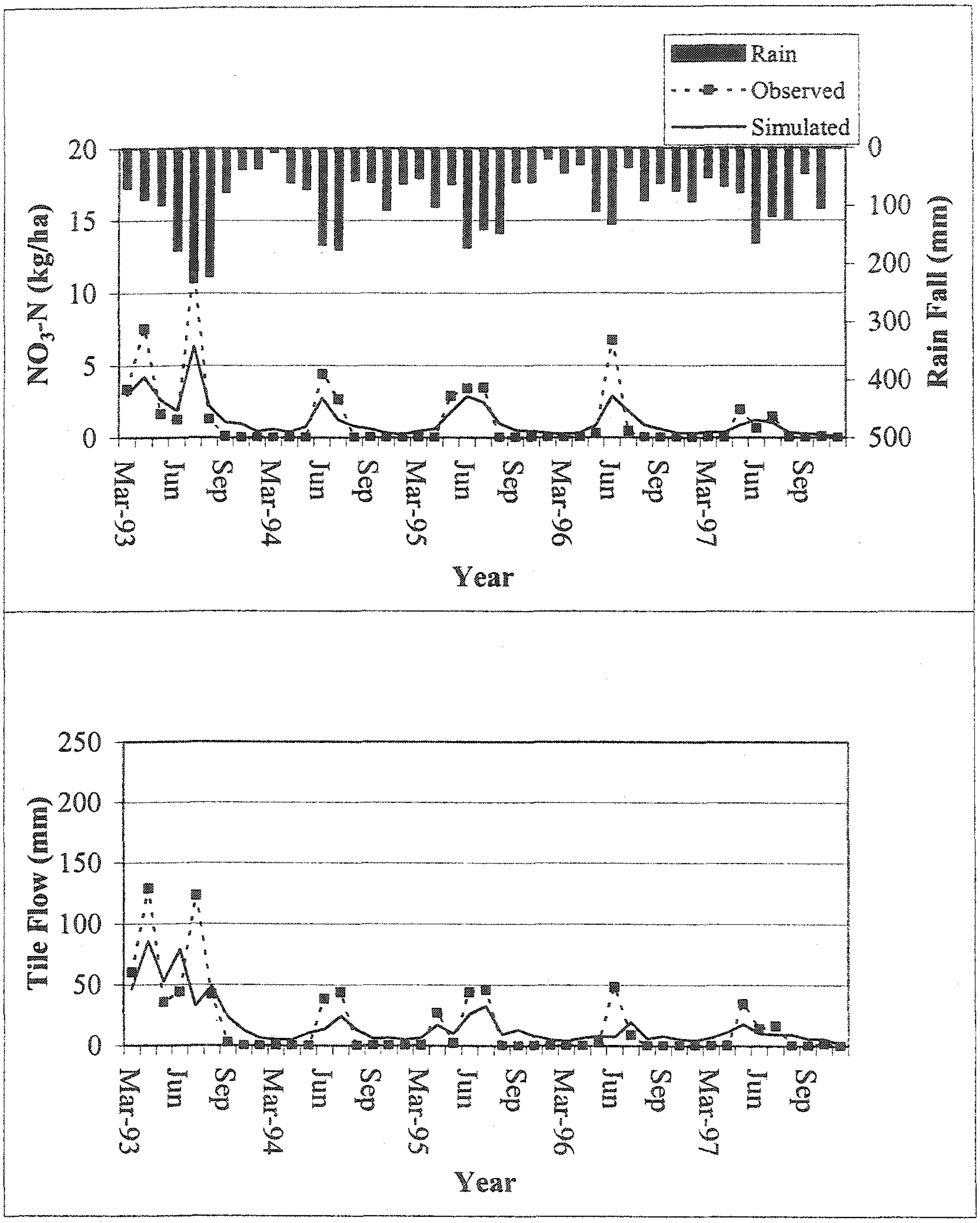
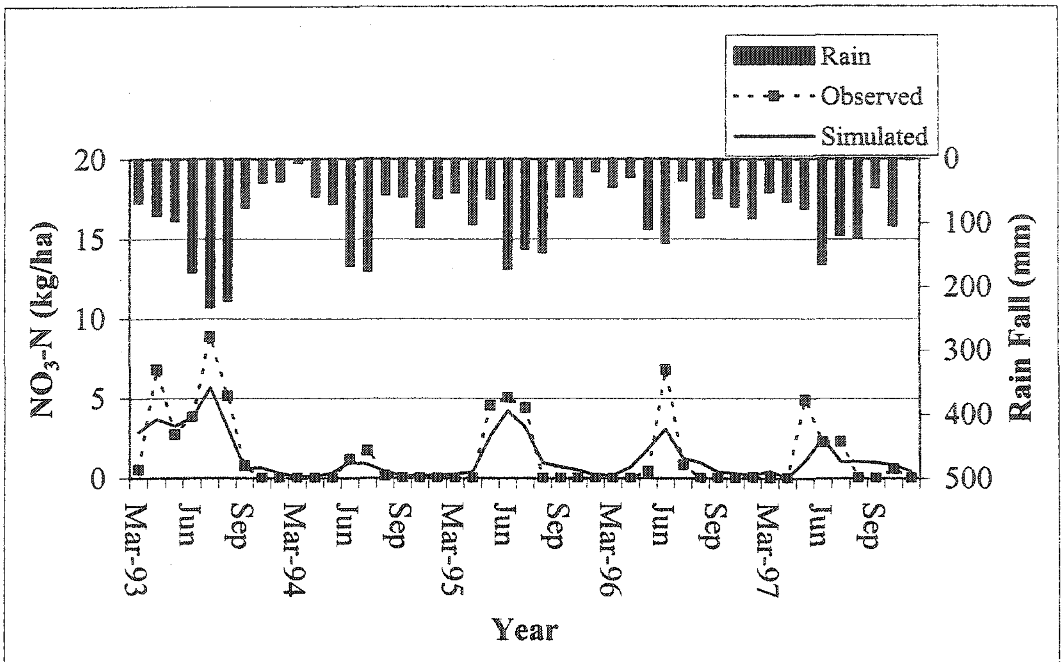



Figure 2. Time series comparisons between measured and simulated monthly for $NO_3$-N losses (kg/ha) with tile flow and for tile flow (mm) during 1993-97 for plot 29



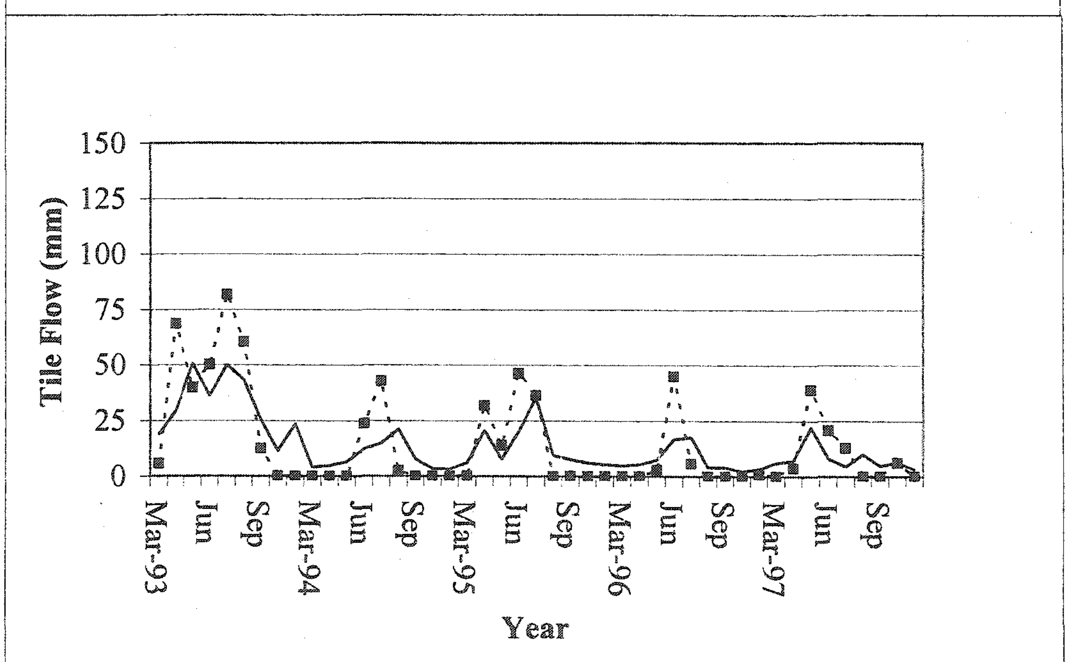




Figure 3. Time series comparisons between measured and simulated monthly for $NO_3$-N losses (kg/ha) with tile flow and for tile flow (mm) during 1993-97 for plot 24

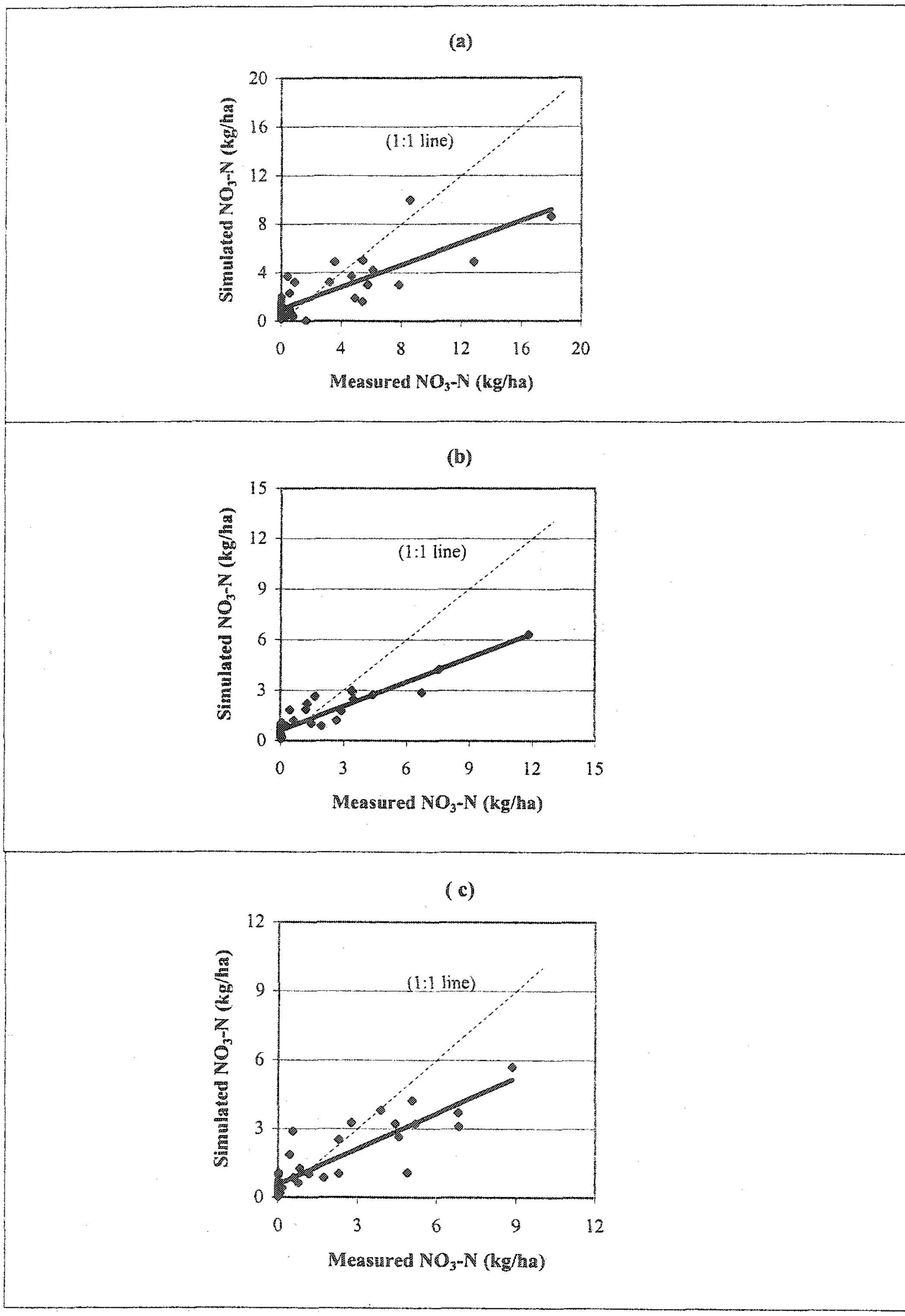



Figure 4. Scattergram comparisons between measured and simulated monthly $NO_3$-N losses (kg/ha) with tile flow during 1993-97 for (a) plot 21 (b) plot 29 ( c) plot 24

# CHAPTER 5. APPLICATION OF THE SWAT MODEL FOR THE UPPER MAQUOKETA RIVER WATERSHED

A paper to be submitted to Journal of the AWRA

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## Abstract

The Upper Maquoketa River Watershed (UMRW) is a mixed livestock production area (dairy, swine, and beef/feeder cattle) that covers over 16,000 ha in northeast Iowa. The dominant land use in the watershed is row crop production of corn and soybeans. Elevated levels of nitrogen have been measured in the UMRW stream system that originate primarily livestock manure and fertilizer applied to cropland. The Soil and Water Assessment Tool (SWAT) model was applied to simulate stream flow and nitrate movement within the UMRW. Stream flow and nitrate data measured in 1999 was used to calibrate the model, and corresponding data collected in 2000 and 2001 was used to validate the model. The model adequately predicted the trends in daily flow, although the peaks were over predicted. The underprediction between the simulated and measured annual average flows for 1999 was

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24%, and 35 and 12% for 2000 and 2001, respectively. The comparison of monthly prediction with measured nitrate values resulted $R^2$ values of 0.94 for calibration year and 0.66 for validation period.

**Keywords:** Modeling, Nutrients, Watershed Management, Water Quality, Flow

**Introduction**

Agriculture, including livestock production, has been implicated as a major source of pollution that impacts water resources. Livestock production has increasingly concentrated in relatively small regions to facilitate feed purchases and other production activities (Purvis, 1998). Confined animal feeding operations and other livestock operations are key agricultural sources of pollution, via nutrient losses from applied animal manure (Edwards et al., 1997). In stream monitoring in the Upper North Bosque River Watershed (UNBRW) has confirmed that the application of dairy manure to crop and pasture land contributes to pollution of the local stream system (McFarland and Hauck, 1999). Many other regions in the United States also have environmental problems due to livestock production including the southern portion of Delaware (Hamilton and Sims, 1995) and the Neuse River Watershed in North Carolina (Warrick and Leavenworth, 1996).

The application of agrochemicals and other fertilizer sources such as manure to intensively cropped areas provide a considerable source of nitrate ($NO_3$-N) that may move to streams through subsurface flow or leach deeper into the soil profile and reach the groundwater system (Jaynes et al., 1999; Kanwar et al., 1999). Over application of nitrogen from fertilizer or manure to continuous corn has been associated with excess residual soil

$NO_3$-N at the end of the growing season which may be more susceptible to leaching over winter when precipitation exceeds evapotranspiration (Katupitiya et al. 1997). The lower nitrogen requirement of corn following soybeans also creates the potential for $NO_3$-N leaching (Lory et al., 1995). In the US Corn Belt, continuous corn has resulted in increased $NO_3$-N concentrations in the soil profile and the tile drainage water along with yields in comparison with corn grown in rotation with soybean (Anderson et al., 1997; Kanwar et al., 1997).

It is too costly, time consuming and spatially impractical in watershed to monitor the water quality continuously. Therefore, mathematical model are among the best tools available for analyzing subsurface flow and contaminants to help the decision-making. The United States Department of Agriculture Agricultural Research Service (USDA-ARS) and other agencies initiated the development of several process based water quality models over the past two decades, in response to the passage of the Clean Water Act in the early 1970s and growing awareness of agricultural nonpoint source pollution (NPS). These models were designed to provide guidance regarding best management practices (BMPs) that can help alleviate NPS pollution at the field- and river basin-scales.

One of the more widely used water quality models is the Soil and Water Assessment Tool (SWAT), which was developed to assess the water quality impacts of agricultural and other land use for a range of watershed scales including large river basins. Detailed documentation on the model inputs is provided in Neitsch et al. (2002a); model theory documentation is presented in Neitsch et al. (2002b) and Arnold et al. (1998). Previous applications of SWAT have compared favorably with measured data for a variety of watershed scales and conditions (Srinivasan and Arnold, 1994; Rosenthal et al., 1995; Arnold and Allen, 1996; Srinivasan et al.,1998; Arnold et al., 1999; Saleh et al., 2000; Santhi et al., 2001).

The objectives of the SWAT applications were

(1) to calibrate the SWAT model by using stream flow and $NO_3$-N load data measured in 1999 at the outlet of the watershed.

(2) to validate the calibrated SWAT model by comparing the predicted versus measured stream flow and $NO_3$-N load data during 2000 and 2001.

## Materials and Methods

### SWAT Model Description

The SWAT model operates on a daily time step and is designed to evaluate management effects on water quality, sediment, and agricultural chemical yield in large ungauged basins. Major model components include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticide, and land management. The local hydrologic response unit (HRU) water balance is represented by snow, soil profile (0-2m), shallow aquifer (2-20m), and deep aquifer (>20m). In this study, the HRU is defined by combination of unique land use and soil type.

SWAT can be executed with historical climate data, generated climate data using an internal weather generator, or a combination of historical and generated inputs. Daily climate data required for SWAT are precipitation, maximum and minimum temperature, relative humidity and wind speed. Historical precipitation and temperature data for two station gauges within the watershed were input into the model; the remaining climate inputs were generated internally in the model.

The hydrology component of SWAT includes surface runoff, percolation, lateral flow, and ground water return flow, evapotranspiration, and channel transmission loss subroutines. Surface runoff is predicted for daily rainfall by using the SCS curve number equation. Ground water flow contribution to total stream flow is simulated by routing a shallow aquifer storage component to the stream. The model offers three options for estimating potential ET: Hargreaves, Priestley-Taylor, and Penman-Monteith. Soil layer data used in SWAT includes layer thickness, sand, silt, clay, bulk density, organic carbon, available water capacity, and hydraulic conductivity.

**Watershed Description**

The SWAT model was applied to the 16,000 ha Upper Maquoketa River Watershed , located within the Maquoketa River Watershed in northeast Iowa (Figure 1). Crop production constitutes approximately 86 percent of the land use. Corn and Soybean are by far the predominant crops, accounting for 66% of the total land use in the watershed. Other key land uses include woodland (8.9%), alfalfa (7.5%), Conservation Reserve Program (CRP) land (4.1%), and pasture (4.0%). A total of 90 operations were identified as having one or more types of livestock in a survey of the UMRW (Osei et al., 2000b), with production focused primarily on swine, dairy cows, beef cattle, feeder cattle, and/or calves and heifers. Surface water monitoring at the four sites (Figure 1) showed elevated levels of nitrate-nitrogen ($NO_3$-N) depending on the flow conditions (Baker et al., 1999). Tile drains are a key conduit of $NO_3$-N to the stream system.

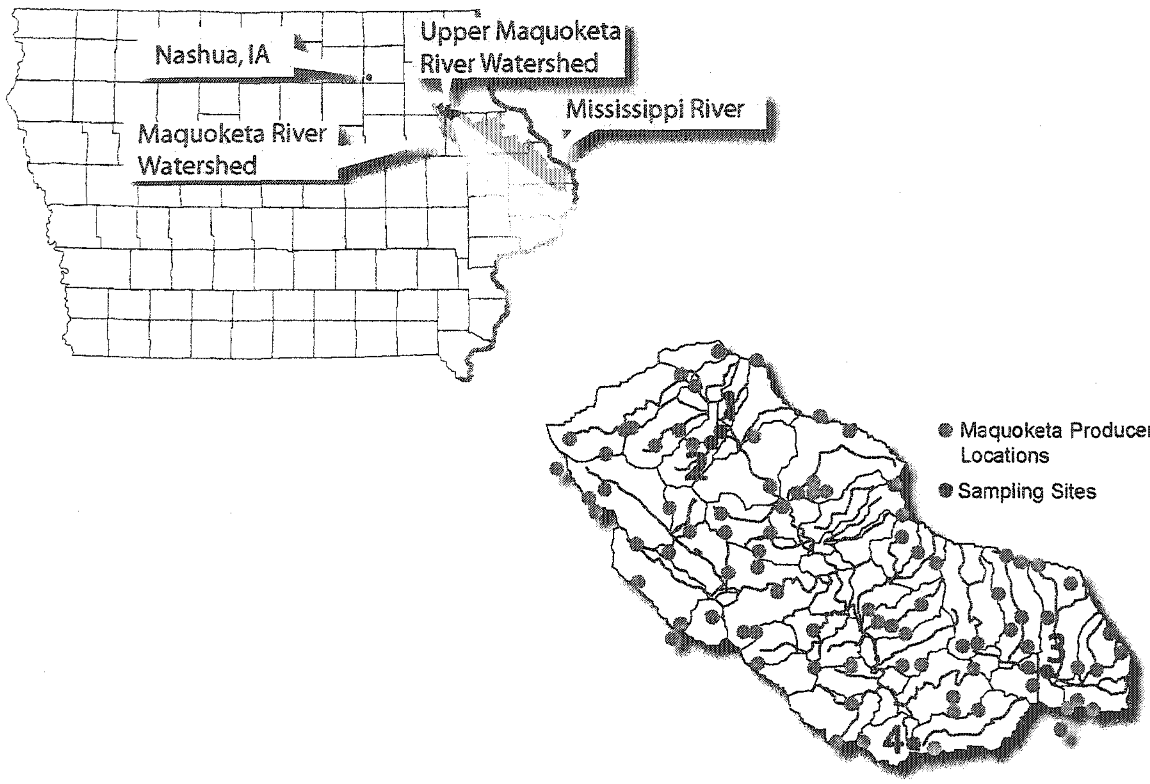


Figure 1. The Upper Maquoketa River Watershed (UMRW) located in northeast Iowa

**Model Input and Simulation Configuration**

The SWAT model requires inputs on weather, topography, soils, land use, management, and stream channels. Land use/cover, topographic, and soil data required by SWAT were originally generated from maps developed within the Geographic Resource Analysis Support System (GRASS) Geographic Information System (GIS) using the GRASS/SWAT Interface program (Gassman et al., 2002). The HRU land use categories generated in SWAT/GRASS included pasture, urban land, continuous corn, corn-soybean, and a five-year rotation of corn and alfalfa. The HRUs were simulated within 52 subwatersheds (Figure 1) that were created based on topographic data contained in GRASS.

The original SWAT cropland HRUs do not include manured cropland; these areas were simulated in the Agricultural Policy Extender (APEX) model (Williams et al., 1995) as described in Gassman et al. (2002). However, these APEX areas were translated into SWAT HRUs for this analysis (Table 2). Relatively small open lot and buffer strip areas that were simulated in APEX for swine open lot and cattle feeder operations (Appendix A) were assumed to be non-grazed pasture areas for the SWAT. Besides these small non-grazed pasture HRUs, the total pasture areas simulated for the relevant SWAT subwatersheds were also split out into separate dairy, calf/heifer, and beef cow pasture HRUs (Table 3) to preserve differences in manure deposition rates and grazing periods that were assumed to occur between these different livestock species.

The manure was assumed to be applied to cropland that was planted in corn. Manure generated by beef pasture and calf/heifer operations was relatively minor compared to the other types of operations and assumed to be deposited on pastures and/or corn fields via grazing rather than applied with a manure spreader. It was assumed that the livestock producers applied solid manure at an annual rate of 44.8 t/ha and liquid manure at the rate of 46,745 l/ha. The majority of the fertilizer applications were applied at the same rate for manured fields relative to nonmanured cropland. An N fertilizer rate of 194 kg/ha was assumed for continuous corn. Assumed fertilizer rates applied to corn following soybean and alfalfa were 128 and 100 kg/ha, respectively, reflecting some accounting of N credit from the legume crops. Additional "crop-removal" N and phosphate ($P_2O_5$) applications of 28 and 68 kg/ha following corn harvest were simulated for continuous corn, corn-soybean, and the second year of corn when rotated with alfalfa for the manured cropland. Smaller starter fertilizer amounts were assumed applied for corn, regardless of manure inputs.

Soil data was obtained from the Iowa Geological Survey and daily precipitation data was obtained from two sites in the watershed. Further discussion of soil type selection, climate inputs and assumptions for UMRW are given in Osei et al. (2000a, 2000b).

### Calibration

Calibration of the SWAT flow and $NO_3$-N load estimates focused on adjusting the curve number (4) and other parameters (Table 5). The criterion used for calibrating the model was to minimize the difference between measured and simulated cumulative annual flow for 1999 and to match the peaks of the simulated daily flow hydrograph with the measured values. A trail and error procedure was used to determine the best curve number values. As pointed out by Duffy et al., (1975), $NO_3$-N concentrations in flow are sensitive to the hydrologic component of a model; therefore, accurate simulation of the various processes of water movement in the soil profile are essential for predicting $NO_3$-N.

After calibrating the model for flow, further effort was made to calibrate the model for $NO_3$-N load by adjusting the *nperco* coefficient, which controls the amount of mineral nitrogen removed from the top 10.0 mm surface layer in the surface runoff relative to the amount removed via percolation. The value of *nperco* can range from 0.0 to 1.0. When *nperco* is 0.0, the concentration of mineral N in the surface runoff is zero. When *nperco* is 1.0, the surface runoff has the same concentration as the percolate. If no value for *nperco* is entered, the model will set *nperco* equal to 0.20. The final calibration step also involved adjusting initial $NO_3$-N concentrations in the soil profile. For calibration and validation of

SWAT model, a user interface (I_SWAT) was used, because It was very convenient and easy to mange the input and output data of a SWAT model.

### Description of the Interactive SWAT (I_SWAT): A User Interface

A single Access® database is used to manage both the input and output data of a SWAT simulation within i_SWAT. This requires the user to convert all existing input data from ASCII files and other file formats into Access. A general schematic of the data flows for the i_SWAT system is shown in Figure 2. An initial preprocessing step is required to fill the Access database tables. Once the input data have been constructed, the SWAT simulation can be executed within i_SWAT. Output data for each simulation is scanned from standard SWAT output files and also stored in the database. The i_SWAT software is accessible at http://www.public.iastate.edu/~elvis by clicking on i_SWAT. A download is also provided for an empty Access database (empty.mdb) that contains the required tables and data columns needed for i_SWAT. Documentation is provided on the website for the structure of the data tables, including the names used in the ACCESS tables for each variable, the equivalent SWAT variable name, the units (if applicable), variable type (integer, etc.), and/or a variable description. Table 1 lists the data tables that are currently included in an Access database for i_SWAT, and the corresponding descriptions and SWAT input or output files. The input data stored in the Access database are translated into the ASCII files required for SWAT when i_SWAT is executed. Several input files are currently not supported by i_SWAT (see Table 1 footnote). Thus these files must be constructed outside of i_SWAT if they are required for a specific SWAT simulation.

The i_SWAT software package translates the input data from an Access® database into the required SWAT input formats, executes SWAT, and extracts and stores desired outputs back into the Access database. A preprocessing process was required prior to using i_SWAT, in which data from databases such as the NRI and CPS were converted from their original formats into tables within the Access database. Storage of the data in Access allows relatively easy modifications of specific input variables, as needed using queries or macros rather than having to make modifications in individual ASCII files. It also provides greater flexibility in viewing and processing input data. Other i_SWAT features include imports of existing SWAT (version 2000 only) datasets, print and print preview options of management system list, charts of output by subbasins or HRUS, and subbasin routing structure maps. The empty.mdb, or other database with the correct structure, must be opened in i_SWAT before importing an existing SWAT dataset. Input files that are not supported by i_SWAT must be copied into the directory where the SWAT simulation is being executed, if the files are needed for the specific SWAT application. The charting functions can be invoked after a successful completion of a SWAT simulation; charting options are accessed by right clicking on the specific chart template. Both a latitude and longitude must be entered for each subbasin (in the database Sub-basin table) in order to create a routing map.

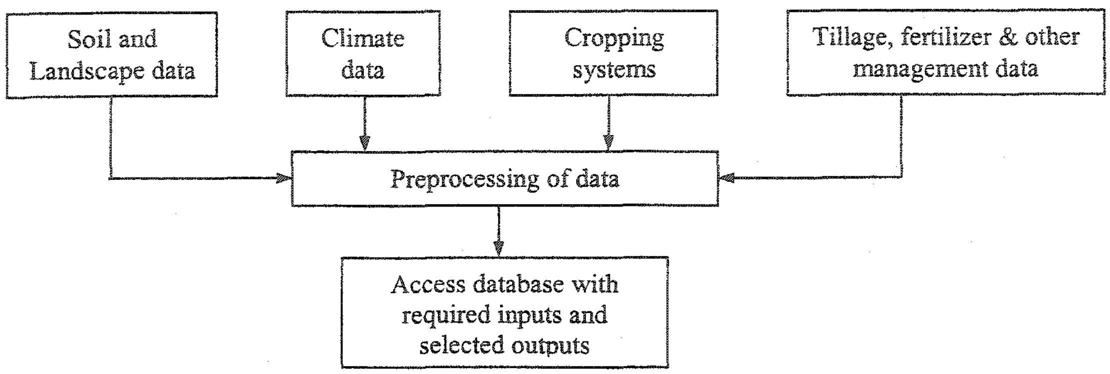


Figure 2. Schematic of i_SWAT system data flows

**Results and Discussion**

The SWAT simulation was executed for a total of 10 years in order to incorporate the full simulation of the five-year corn and alfalfa rotation. However, the results of the SWAT simulation are only shown for 1999-2001, which were the three years that measured data were collected for. Calibration of SWAT was performed for 1999 while 2000 and 2001 were used as the validation years.

Figure 3 shows the comparison between the SWAT daily flow estimates and the measured daily flows for the 1999 water year. The model accurately tracked most of the peak flow events that occurred during the year, although the peaks were usually over-predicted. The simulated peak flows sometimes occurred a day earlier than observed, which may be a result of the model's inability to predict the surface and subsurface interaction associated with the topography and the effect of rainfall timing. The simulated recession curves were adequate but often faster than the observed recession curves. Closer inspection of the data indicated that SWAT estimated the peaks and recession curves well except during the summer season. A comparison of the monthly measured and predicted flows for the calibration year is shown in Figure 4. The majority of the low-flow periods were under-predicted by SWAT. The cumulative annual predicted flow was about 24% lower than the corresponding total annual measured flow (Table 6).

The time series (Figure 5) comparison for the validation period of 2000 and 2001 shows that SWAT generally tracked the measured flow very well. However, the time-series results also clearly show that most of the peaks were over-predicted. The peak flows predicted by SWAT usually occurred on the same day they were actually observed, but some predicted peaks occurred during low flow periods. Figure 6 shows the monthly measured and predicted flows for the validation period. The majority of the flow was under-predicted by SWAT in contrast to the over-predicting of the peaks. The flow was under-predicted by 37 and 12% for the year of 2000 and 2001, respectively. Coefficient of determination ($R^2$) values of 0.98 and 0.75 were calculated for the monthly flow estimates (Figures 7 and 8) for the calibration and validation periods, respectively, indicating that model accurately replicated the monthly measured flow trends.

Simulated and measured daily $NO_3$-N loads are shown in Figures 9 and 10 for the calibration and validation periods. The model tracked most of the $NO_3$-N peak events that occurred during the year, although the peaks were usually greatly over-predicted especially for the validation period. Goolsby et al. (2001) reported that higher stream flow could influence $NO_3$-N in two ways. First, the volume of flow can be larger and more $NO_3$-N will be transported unless concentrations decrease. Second, the higher precipitation would leach more accumulated $NO_3$-N from soils and would actually cause $NO_3$-N concentrations to increase. Also Bakhsh et al. (2002) reported a significant linear relationship between growing season precipitation and subsurface drainage volume and also a significant relationship between subsurface drainage volume and $NO_3$-N leaching losses with subsurface drainage water.

The $NO_3$-N was over predicted by 25%, 22% and 108% for 1999, 2000, and 2001 (Table 7). The $NO_3$-N load over-predictions usually occurred during the months of April, May and June (Figures 11 and 12). The $NO_3$-N trend was poorly tracked by SWAT, as reflected in the $R^2$ value of 0.96 and 0.56 for calibration and validation period respectively (Figure 13 and 14).

**Summary and Conclusions**

The SWAT model was used to estimate the flow and nitrate loading for UMRW watershed. The model was calibrated for stream flow and nitrate data measured in 1999 at the outlet of the watershed and model was validated for 2000 and 2001 period. The application of SWAT for the UMRW indicates that the model accurately tracked most of the peak flow events that occurred during the year, although the peaks were usually over predicted. The simulated recession curves were adequate but often faster than the observed recession curves. Closer inspection of the data indicated that SWAT model estimated peaks and recession curves well except during the summer season. The model tracked the flow reasonably well but model was unable to track the nitrate trend. The overprediction between the simulated and measured annual flow for year 1999 was 24%, while 35% for year 2000 and 12% for year 2001. The $NO_3$-N was over predicted by 92%, 50% and 200% for 1999, 2000, and 2001. The $NO_3$-N load over-predictions usually occurred during the months of April, May and June. The $NO_3$-N trend was poorly tracked by SWAT, as reflected in the $R^2$ value of 0.96 and 0.56 for calibration and validation period respectively.

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Table 1. List of tables currently in Access database used by I_SWAT

| Database table | Description | SWAT files[a] |
|---|---|---|
| **Input data** | | |
| Control Records | Input control codes and basin-level parameters | .cod, .bsn |
| Crop | Crop/plant growth parameters | Crop.dat |
| Fertilizer | Fertilizer and manure nutrient contents | fert.dat |
| HRU | Characteristics for each HRU | .hru, .gw |
| Management | Management data for each HRU | .mgt |
| Pesticides | Degradation and other pesticide characteristics | pest.dat |
| Point Sources | Point source loading data by subbasin | .pcs |
| Pond | Pond and wetland data by subbasin | .pnd |
| Reservoir | Reservoir characteristics by subbasin | .res |
| Routing | Contains data for the watershed configuration file | .fig |
| Soil layers | Soil layer data required by HRU | .sol |
| Soils | Soil name; misc. soil data by HRU | .sol |
| Stream Water Quality | Initial in-stream water quality data by subbasin | .swq |
| Sub-basins | Subbasin area, channel, and related data | .sub, .rte |
| Tillage | Residue mixing depth, etc. for tillage equipment | Till.dat |
| Urban | Urban build-up/wash-off of solids data | urban.dat |
| Water Use | Consumptive water use data by subbasin | .wus |
| Weather by Month | Monthly weather and wind statistics | .wgn |
| Weather Historical | Daily historical precipitation and temperature data | .pcp, .tmp |
| Weather Stations | Weather station coordinates and elevations | .wgn |
| **Output data** | | |
| Output HRU Annual | HRU outputs (under development) | .sbs |
| Output Reach | Daily, monthly, or annual outputs at subbasin outlets | .rch |
| **Miscellaneous** | | |
| Help Text | i_SWAT variable descriptions (under development) | - |

[a]The input files are created from the corresponding Access tables; the Access output tables are filled from the corresponding SWAT output files. The file.cio is created by i_SWAT when a SWAT run is executed; the .slr, .wnd, .hmd, .pet, .wwq, .chm, .lwq, recday.dat, recmon.dat and reccnst.dat files are currently not supported by i_SWAT and must be constructed by the user.

Table 2. Cropland HRU areas (ha)

| Sub-watershe | Continuous corn (beef)a | Continuous corn | Corn-soybean | Soybean-corn | CCAAAb | AAACCb |
|---|---|---|---|---|---|---|
| 1 | | 41.2 | 2.7 | 2.7 | 50.6 | 50.6 |
| 5 | | 6.8 | 6.8 | 6.8 | | |
| 6 | 65.6 | 8.5 | 8.5 | 8.5 | | |
| 7 | 91.1 | 26.0 | | | 34.1 | 34.1 |
| 8 | | 21.7 | 18.7 | 18.7 | 4.0 | 4.0 |
| 10 | 25.5 | 52.4 | 18.5 | 18.5 | 44.5 | 44.5 |
| 11 | | 41.8 | | | 54.9 | 54.9 |
| 12 | | 5.1 | 5.1 | 5.1 | | |
| 13 | 60.7 | | | | | |
| 15 | | 13.2 | | | 17.4 | 17.4 |
| 16 | | 32.4 | 32.4 | 32.4 | | |
| 17 | | 51.7 | 31.9 | 31.9 | 26.0 | 26.0 |
| 22 | | 13.2 | | | 17.4 | 17.4 |
| 23 | | 15.4 | | | 20.2 | 20.2 |
| 24 | | 32.2 | 32.2 | 32.2 | | |
| 27 | | 18.5 | 18.5 | 18.5 | | |
| 28 | | 66.3 | 13.5 | 13.5 | 69.4 | 69.4 |
| 29 | | 43.9 | 28.5 | 28.5 | 20.2 | 20.2 |
| 30 | | 4.0 | 2.7 | 2.7 | 1.7 | 1.7 |
| 31 | | 61.8 | | | 81.3 | 81.3 |
| 32 | | 15.4 | | | 20.2 | 20.2 |
| 33 | 30.4 | | | | | |
| 34 | | 41.4 | 41.4 | 41.4 | | |
| 35 | | 58.5 | | | 76.9 | 76.9 |
| 36 | 42.5 | | | | | |
| 40 | | 51.0 | 12.2 | 12.2 | 50.9 | 50.9 |
| 41 | | 104.6 | 74.9 | 74.9 | 39.0 | 39.0 |
| 42 | 24.3 | | | | | |
| 43 | 36.4 | 20.5 | | | 26.9 | 26.9 |
| 44 | | 66.8 | 59.3 | 59.3 | 9.8 | 9.8 |
| 45 | | 13.2 | | | 17.4 | 17.4 |
| 46 | | 114.5 | 114.5 | 114.5 | | |
| 47 | | 23.1 | 7.7 | 7.7 | 20.2 | 20.2 |
| 49 | | 27.8 | 27.8 | 27.8 | | |
| 51 | | 13.6 | 0.0 | 0.0 | 17.9 | 17.9 |
| 52 | | 6.1 | 6.1 | 6.1 | | |

[a] Continuous corn (beef) refers to continuous corn fields that beef cattle were assumed to graze for a six month period from October 19 to April 15 of each year

[b] CCAAA and AAACC represents corn-corn-alfafla-alfalfa-alfalfa and alfafla-alfalfa-alfalfa-corn-corn

Table 3. Pasture HRU areas (ha)

| Sub-watershed | Total Area | Non-grazed [a] | Dairy Cow | Calf/heifer | Beef cow |
|---|---|---|---|---|---|
| 1 | 31.2 | 1.5 | 23.6 | 6.1 | |
| 5 | 0.3 | 0.3 | | | |
| 6 | 21.9 | | | | 21.9 |
| 7 | 50.1 | 1.0 | 15.9 | 2.8 | 30.4 |
| 8 | 2.9 | 0.1 | 2.7 | | |
| 10 | 30.6 | 1.3 | 20.8 | | 8.5 |
| 11 | 27.3 | 1.6 | 25.6 | | |
| 12 | | | | | |
| 13 | 20.2 | | | | 20.2 |
| 15 | 8.6 | 0.5 | 8.1 | | |
| 16 | 1.4 | 1.4 | | | |
| 17 | 14.8 | 0.8 | 13.2 | 0.8 | |
| 22 | 8.6 | 0.5 | 8.1 | | |
| 23 | 18.1 | 0.6 | 9.4 | 8.1 | |
| 24 | | | | | |
| 27 | 0.4 | 0.4 | | | |
| 28 | 35.0 | 2.0 | 33.0 | | |
| 29 | 10.6 | 0.6 | 10.0 | | |
| 30 | 1.0 | 0.1 | 1.0 | | |
| 31 | 40.3 | 2.4 | 37.9 | | |
| 32 | 10.0 | 0.6 | 9.4 | | |
| 33 | 10.1 | | | | 10.1 |
| 34 | 1.5 | 0.2 | 1.3 | | |
| 35 | 38.2 | 2.3 | 35.9 | | |
| 36 | 14.2 | | | | 14.2 |
| 40 | 25.6 | 1.8 | 23.7 | | |
| 41 | 19.7 | 1.1 | 18.6 | | |
| 42 | 8.1 | | | | 8.1 |
| 43 | 25.5 | 0.8 | 12.5 | | 12.1 |
| 44 | 13.6 | 0.3 | 5.2 | 8.1 | |
| 45 | 8.6 | 0.5 | 8.1 | | |
| 46 | | | | | |
| 47 | 20.6 | 0.7 | 9.8 | 10.1 | |
| 49 | 1.1 | 0.0 | 1.1 | | |
| 51 | 8.9 | 0.6 | 8.4 | | |
| 52 | 0.2 | 0.2 | | | |

[a] The non-grazed pasture HRUs consists of area that were simulated as open lots and buffer strips

Table 4. Curve numbers assumed in SWAT

| Land use | Curve number |
|---|---|
| Continuous corn | 78 |
| Corn-soybean or soybean-corn | 78 |
| CCAAA or AAACC[a] | 70 |
| Hay and pasture | 64 |
| Forest | 62 |
| Urban | 90 |

[a] CCAAA and AAACC represents corn-corn-alfafla-alfalfa-alfalfa and alfafla-alfalfa-alfalfa-corn-corn rotation

Table 5. Final values of additional parameters that were used in simulation

| Input parameters | Value |
|---|---|
| Surface runoff lag time (days) | 0.1 |
| Ground wate delay | 20 |
| Baseflow factor | 0.2 |
| Ground water revap coefficient | 0.2 |
| Nitrogen Percolatin coefficient (nperco) | 0.01 |

Table 6. Annual observed and simulated flow (mm)

| Year | Measured | Simulated | %D |
|---|---|---|---|
| 1999 | 373.91 | 283.45 | -24.19 |
| 2000 | 315.50 | 197.24 | -37.48 |
| 2001 | 332.13 | 292.06 | -12.06 |

Table 7. Annual measured and simulated $NO_3$-N load (kg/ha)

| Year | Measured | Simulated | %D |
|---|---|---|---|
| 1999 | 38.54 | 47.99 | 24.53 |
| 2000 | 38.25 | 46.78 | 22.31 |
| 2001 | 36.22 | 75.26 | 107.82 |

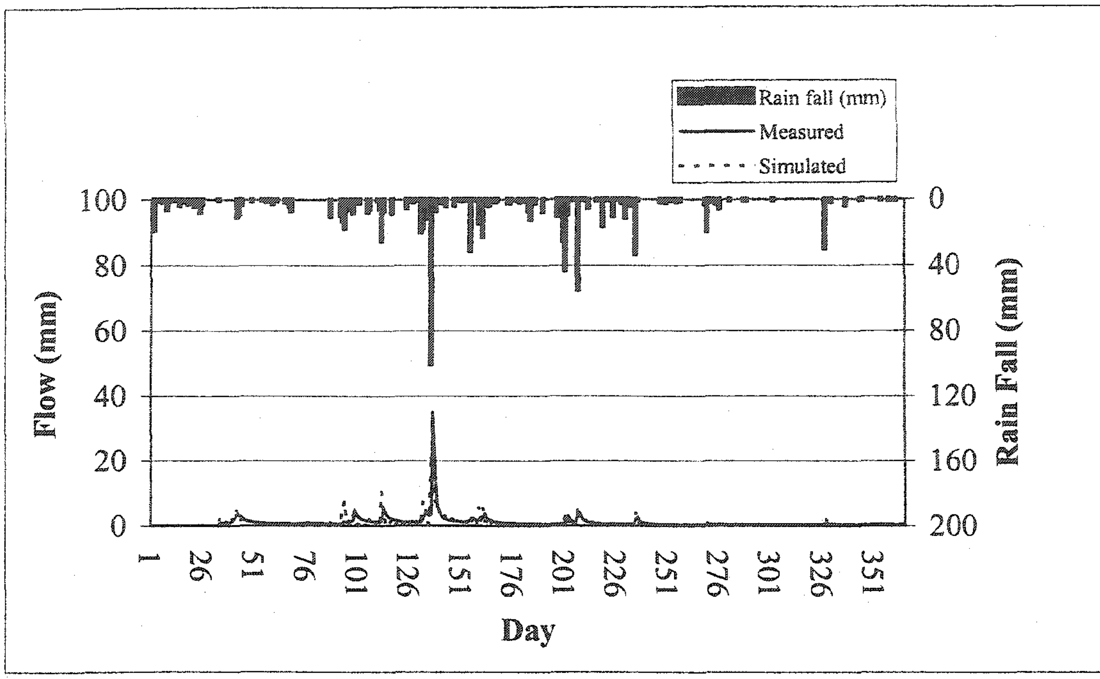


Figure 3. Observed and simulated daily flow for 1999

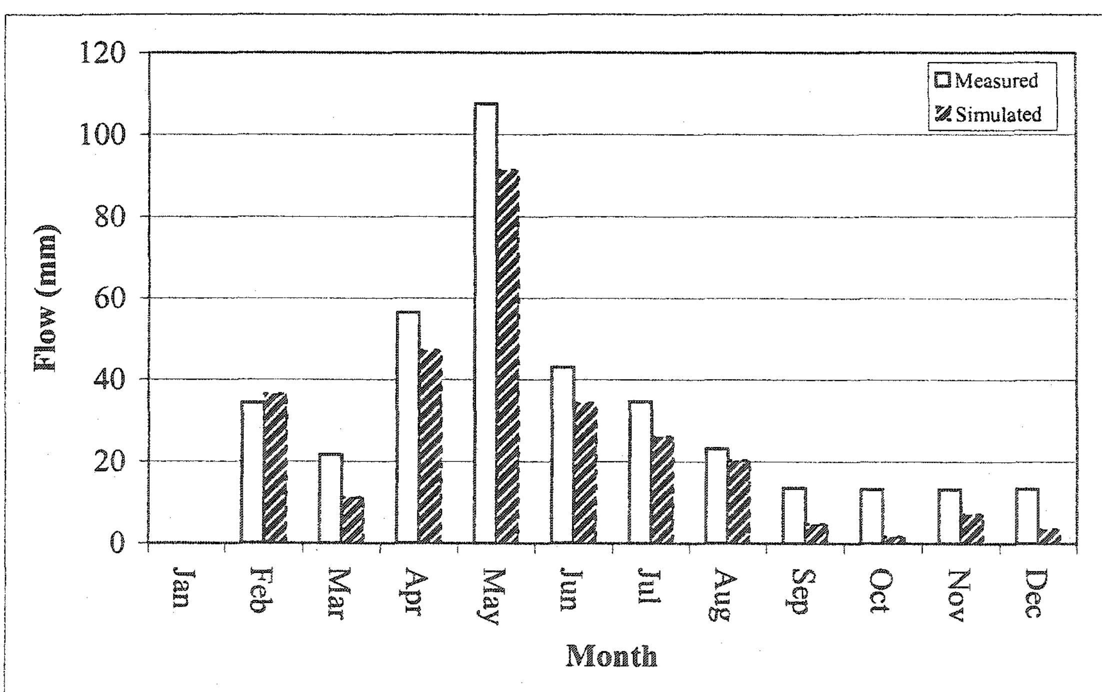


Figure 4. Observed and simulated monthly flow for 1999

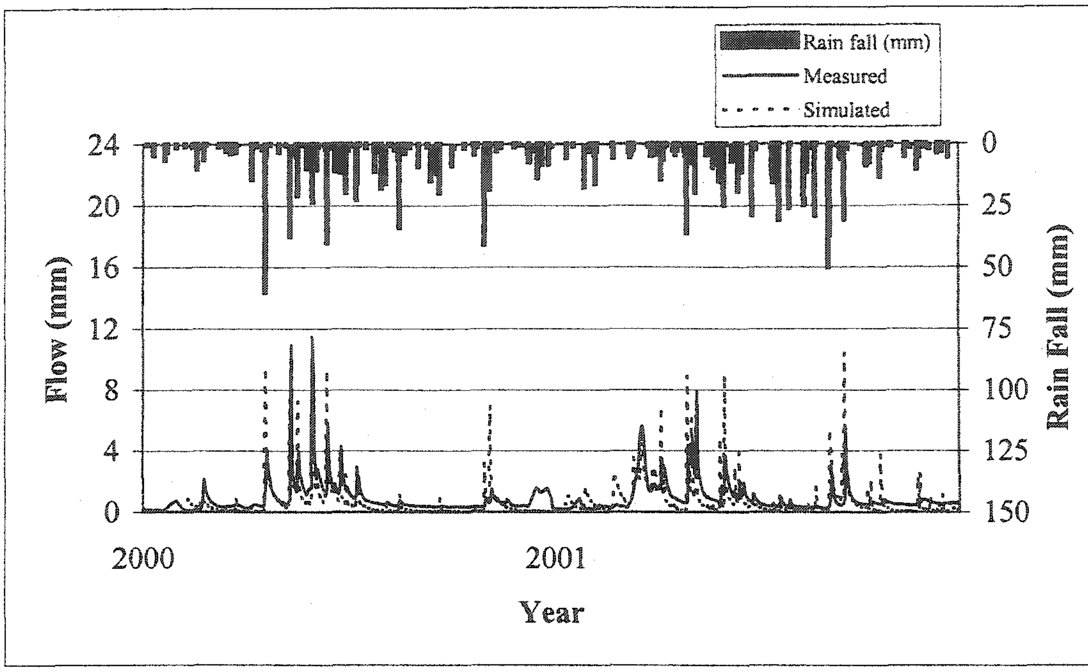


Figure 5. Observed and simulated daily flow for 2000-2001

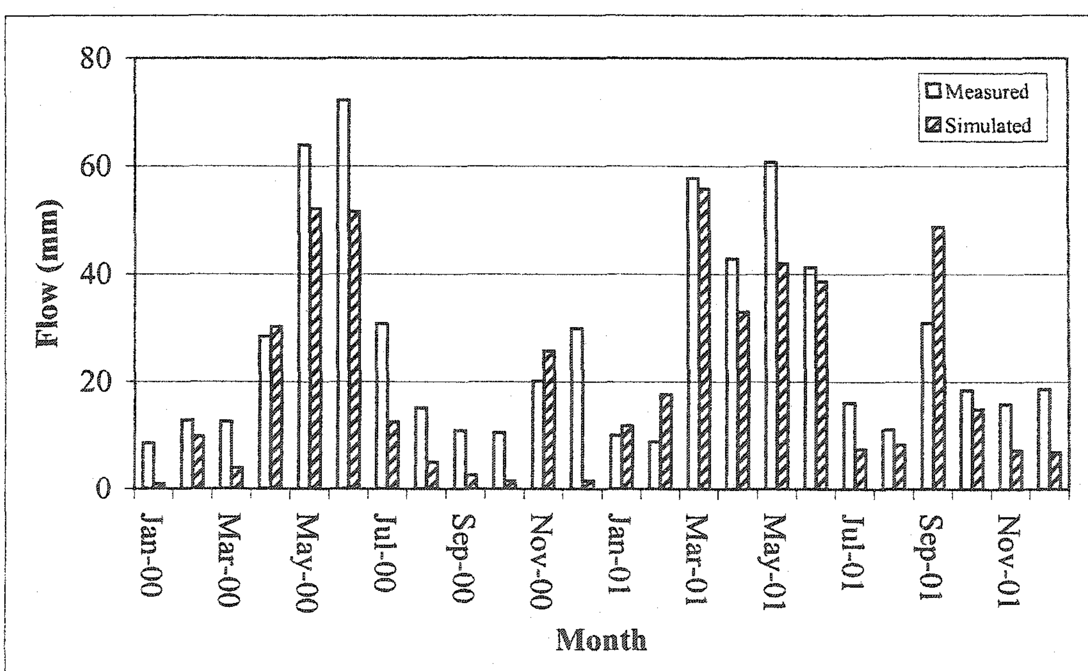


Figure 6. Observed and simulated monthly flow for 2000-2001

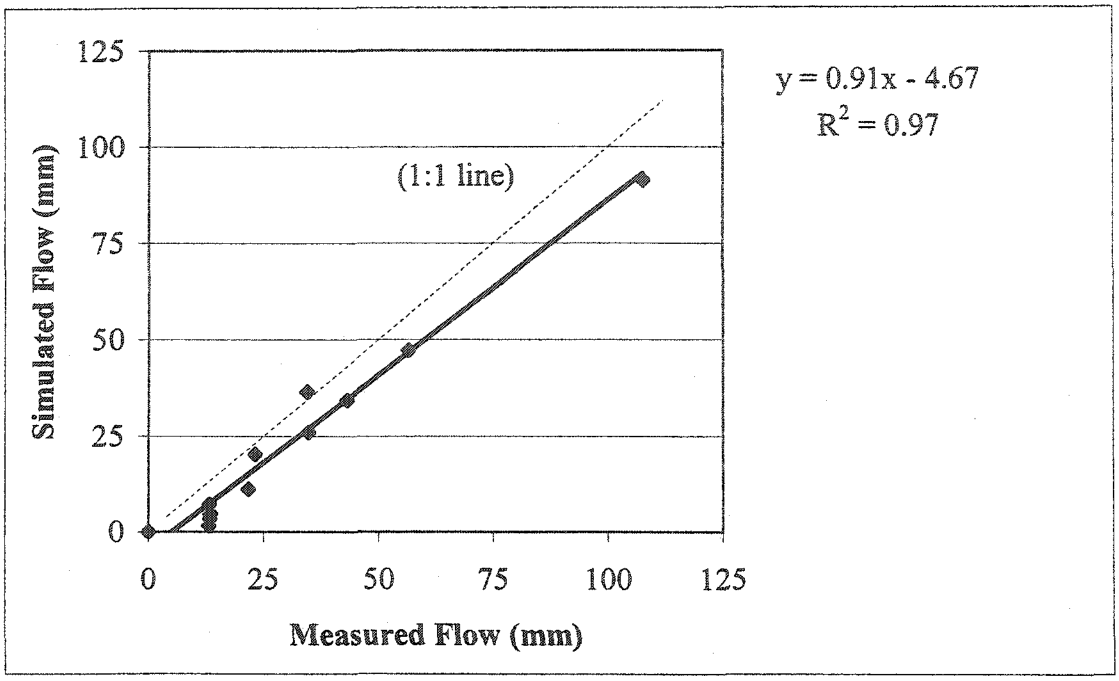


Figure 7. Coefficient of determination ($R^2$) for measured monthly flow relative to simulated monthly flow for 1999

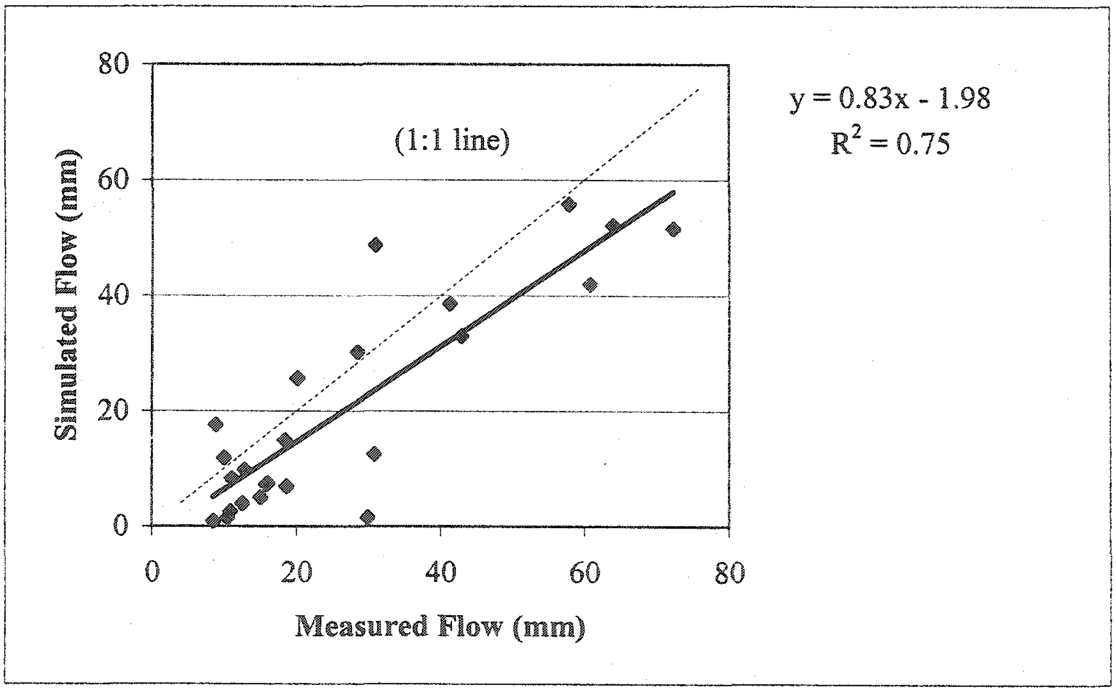


Figure 8. Coefficient of determination ($R^2$) for measured monthly flow relative to simulated monthly flow for 2000-2001

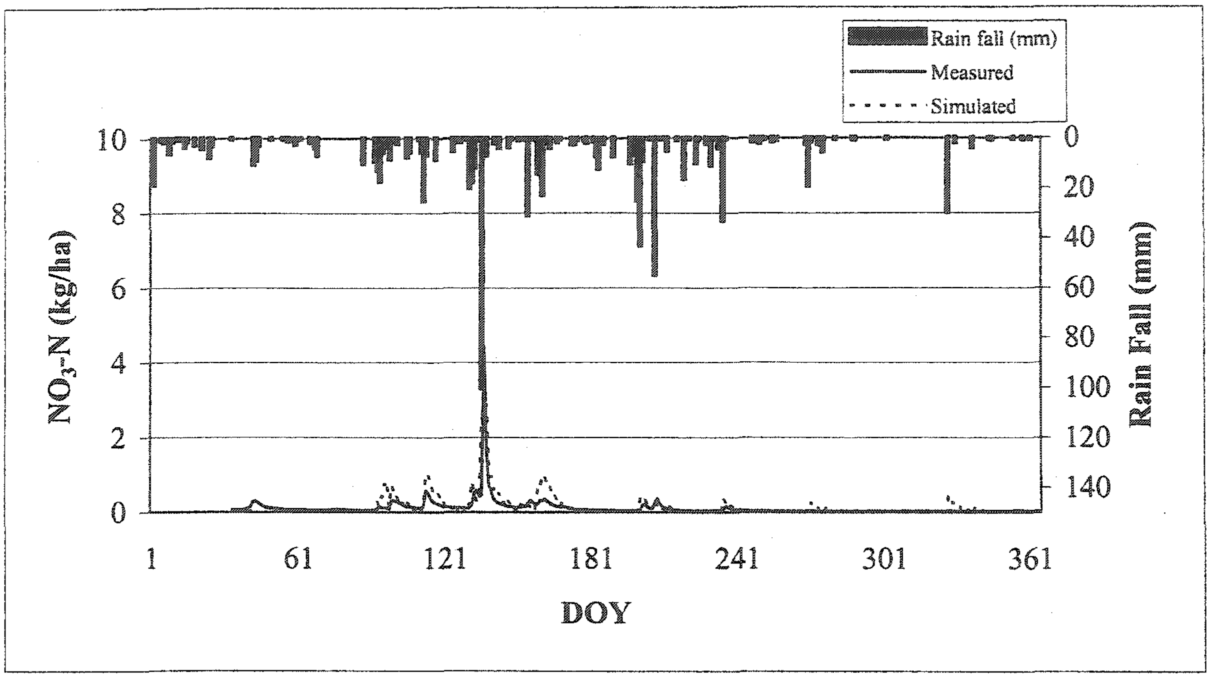


Figure 9. Observed and simulated daily $NO_3$-N load for 1999

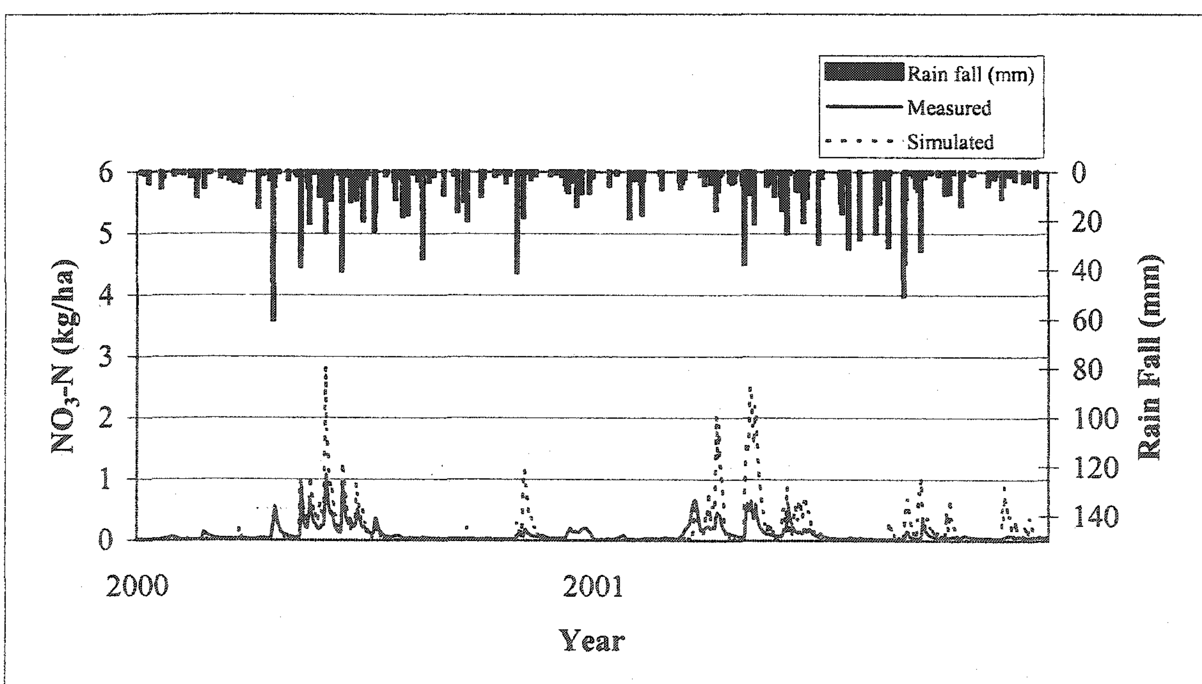


Figure 10. Observed and simulated daily $NO_3$-N load for 2000-2001

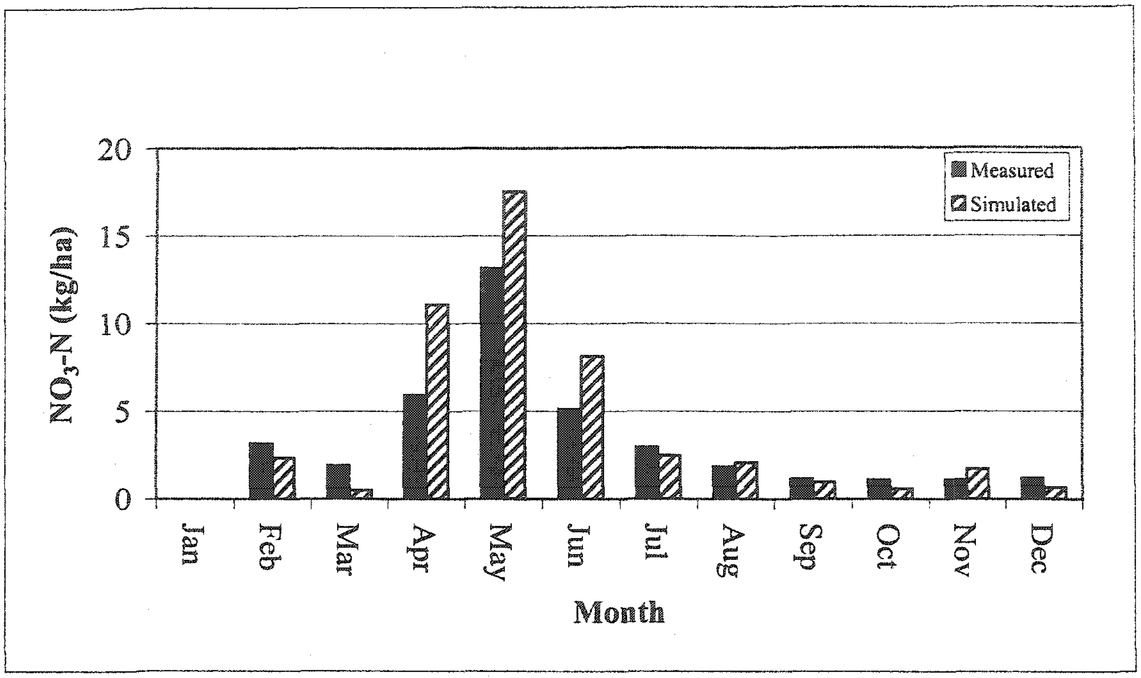


Figure 11. Observed and simulated monthly $NO_3$-N load for 1999

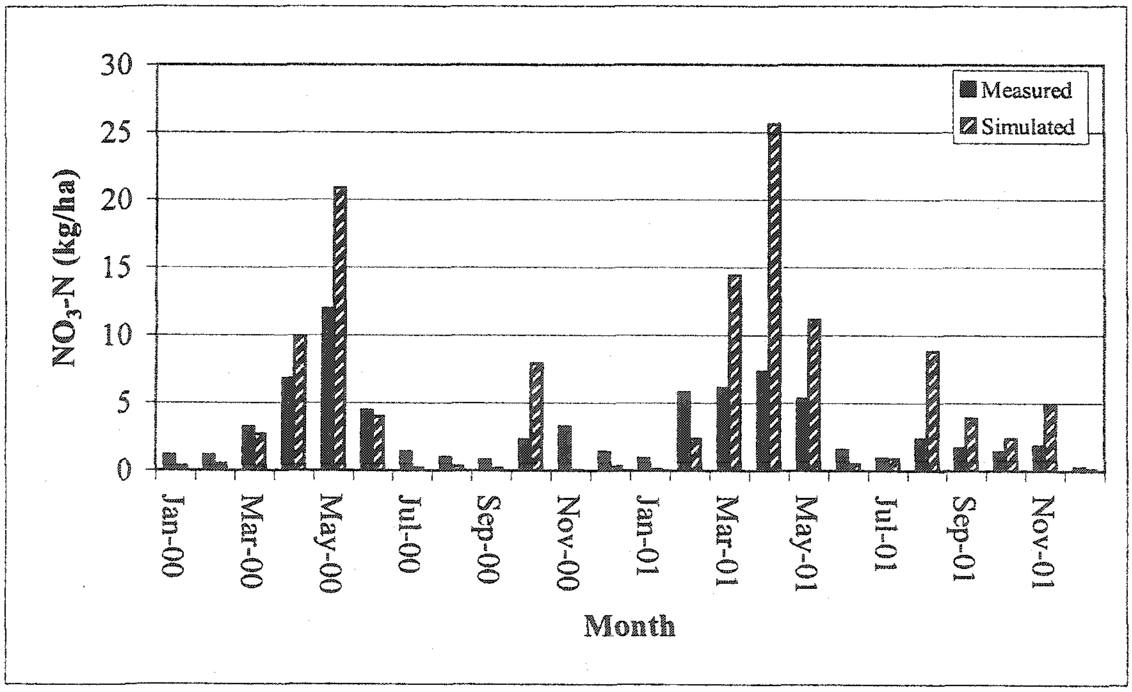


Figure 12. Observed and simulated monthly $NO_3$-N load for 2000-2001

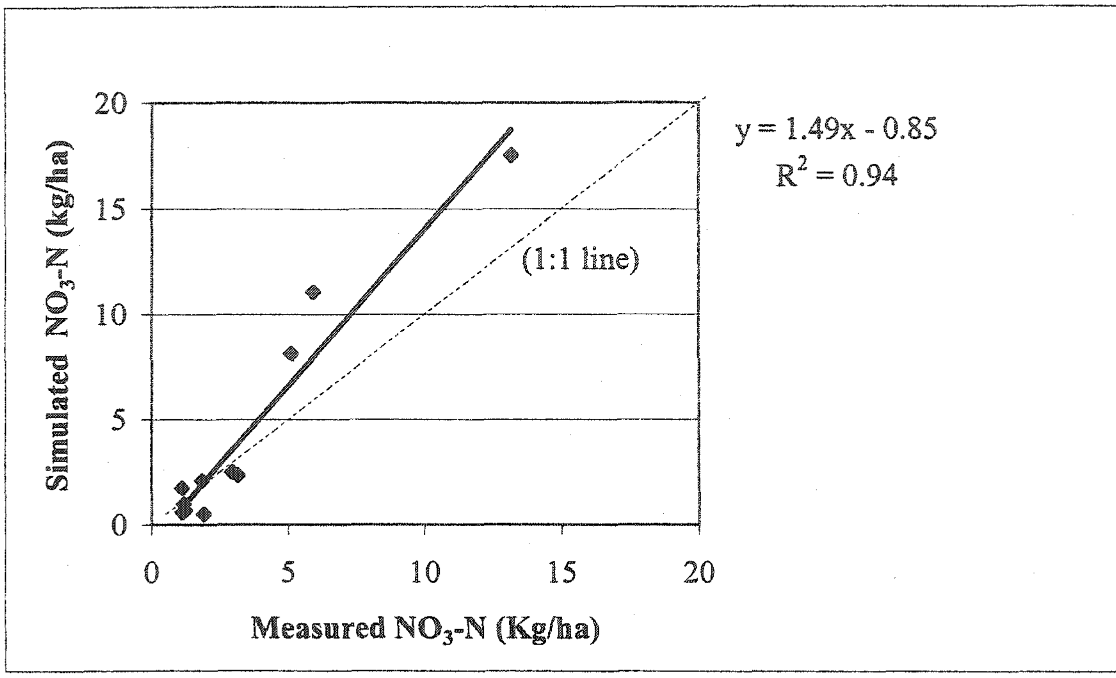


Figure 13. Coefficient of determination ($R^2$) for measured monthly $NO_3$-N load relative to simulated monthly $NO_3$-N load for 1999

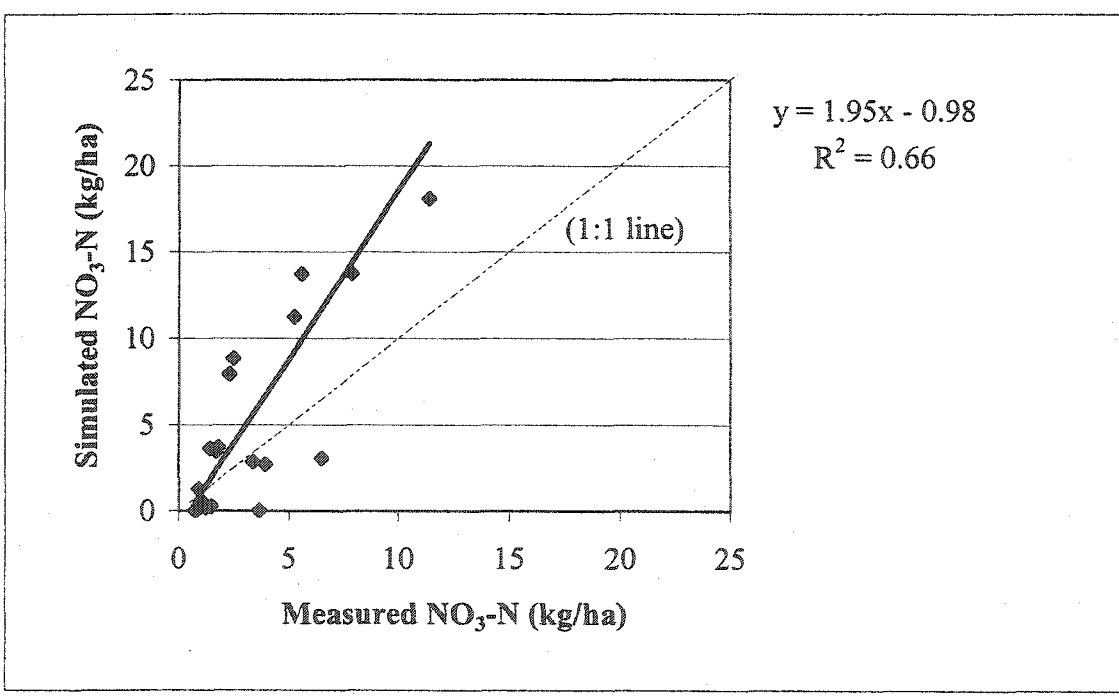


Figure 14. Coefficient of determination ($R^2$) for measured monthly $NO_3$-N load relative to simulated monthly $NO_3$-N load for 2000-2001

# CHAPTER 6. GENERAL CONCLUSIONS

1. The SWAT model accurately tracked the observed monthly trends of tile flow for the calibration year as evidenced by the $r^2$ values that ranged between 0.70 and 0.97 and the E values that were between 0.52 and 0.68. The simulated tile flows followed the trends of observed flows reasonably well for the validation period, but the $r^2$ (0.49 to 0.67) and E (0.47 to 0.67) values were weaker than those determined for the calibration period. The model under-estimated the monthly flows and predicted low levels of flow to occur during periods in which no flow was observed. The under-estimation of the peak flows could be due to the fact that macropore flow is not accounted for in SWAT. Observations at the site indicate that macropore flow may be an important component of peak flow periods.
2. A comparison between the predicted annual $NO_3$-N losses with tile flow for the calibration year (1995) and the corresponding observed values resulted in relatively low $D_v$ values that ranged from -7.34 to 5.50. These $D_v$ values indicate that the model simulated close to the measured values for the total $NO_3$-N losses for 1995. The predicted annual $NO_3$-N losses with tile flow for the four validation years were not close to the measured values, especially for 1994 and 1997, as reflected by $D_v$ values that ranged from about 7.2 to 20.4. The results revealed that the model was unable to predict the magnitude of the peak flow months in each of the five simulated years. The model also predicted low levels of $NO_3$-N losses in tile flow during periods in which no $NO_3$-N loss in tile flow was observed. These discrepancies between the predicted and observed $NO_3$-N losses with tile flow are in part due to complexities

introduced by SWAT's hydrologic computations. These errors were further compounded by weaknesses in the model in capturing the complete nitrogen cycle that occurs in soils cropped with row crops such as corn and soybean.

3. The model was calibrated for stream flow and nitrate data measured in 1999 at the outlet of the watershed and model was validated for 2000 and 2001 period. The application of SWAT for the UMRW indicates that the model accurately tracked most of the peak flow events and recession curves well except during the summer season. Model did not perform well in predicting the nitrate-nitrogen losses with stream flow. The $NO_3$-N was over predicted by 25%, 22% and 108% for 1999, 2000, and 2001 respectively. Higher stream flow could influence $NO_3$-N in two ways. First, the volume of flow can be larger and more $NO_3$-N will be transported unless concentrations decrease. Second, the higher precipitation would leach more accumulated $NO_3$-N from soils and would actually cause $NO_3$-N concentrations to increase.

**Recommendations For Future Work**

Although SWAT model showed a good potential for simulating subsurface drain flow under different tillage systems, a number of changes would be necessary to improve the prediction of the model.

1. Further research is needed to better quantify why SWAT is under-predicting the cumulative monthly tile flows and over-predicting monthly flow during the periods in which little or no flow was occurring. Significant improvement in SWAT's tile flow prediction capabilities has occurred for an application of a test version of the model

(not yet publicly released) for a watershed in Iowa (Arnold, J.G. Personal communication. Grassland, Soil and Water Research Laboratory, USDA-ARS, Temple, TX). Also due to significant weaknesses in SWAT 99.2's ability to track all components of nitrogen movement to tile flow in crop fields. Further research work is needed, with more current versions of SWAT, to improve the accuracy of the results reported here.

2. All available computer simulation models have certain components which may not be able to simulate certain processes to make reliable predictions for all environmental conditions. Therefore, calibration and validation with locally available data is very important. Future research needs to be expanded to a larger landscape scale and would like to see another project where similar water quality data are collected over a watershed scale.

## Appendix A. Areas of crop fields and associated soil type and landscape parameters simulated in SWAT

| Farm ID | SWAT sub-basin | Farm type | Openlot (ha) | Grass buffer (ha) | CCCCCC (ha) | CSCSCS (ha) | SCSCSC (ha) | CCAAA (ha) | AAACC (ha) | Pasture (ha) | Manure appl. rate (kg/ha) | Fert file # | S5 ID | Soil map unit ID | Slope length (m) | Slope (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 7 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.834 | 3764 | 17 | IA0046 | 84 | 55 | 2 |
| 2 | 7 | 1 | 0.488 | 0.112 | 15.394 | 0 | 0 | 20.244 | 20.244 | 9.446 | 6273 | 21 | IA0046 | 84 | 55 | 2 |
| 3 | 7 | 2 | 0 | 0 | 91.093 | 0 | 0 | 0 | 0 | 30.364 | 6587 | 16 | IA0046 | 84 | 55 | 2 |
| 4 | 7 | 1 | 0.335 | 0.093 | 10.556 | 0 | 0 | 13.881 | 13.881 | 6.477 | 6273 | 22 | IA0046 | 84 | 55 | 2 |
| 5 | 8 | 4 | 0.177 | 0.067 | 5.137 | 5.137 | 5.137 | 0 | 0 | 0 | 6587 | 23 | IA0046 | 84 | 55 | 2 |
| 6 | 1 | 1 | 0.474 | 0.11 | 14.954 | 0 | 0 | 19.665 | 19.665 | 9.176 | 6273 | 24 | IA0046 | 84 | 55 | 2 |
| 7 | 1 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6.073 | 3764 | 17 | IA0046 | 84 | 55 | 2 |
| 8 | 8 | 4 | 0.465 | 0.109 | 13.518 | 13.518 | 13.518 | 0 | 0 | 0 | 6587 | 20 | IA0046 | 84 | 55 | 2 |
| 9 | 1 | 1 | 0.746 | 0.138 | 23.53 | 0 | 0 | 30.944 | 30.944 | 14.439 | 6273 | 25 | IA0046 | 84 | 55 | 2 |
| 10 | 1 | 3 | 0.046 | 0.034 | 2.679 | 2.679 | 2.679 | 0 | 0 | 0 | 5870 | 5 | IA0046 | 84 | 55 | 2 |
| 11 | 5 | 4 | 0.232 | 0.077 | 6.759 | 6.759 | 6.759 | 0 | 0 | 0 | 6587 | 20 | IA0046 | 84 | 55 | 2 |
| 12 | 17 | 3 | 0 | 0 | 5.088 | 5.088 | 5.088 | 0 | 0 | 0 | 6119 | 10 | IA0046 | 84 | 55 | 2 |
| 13 | 17 | 4 | 0.869 | 0.149 | 25.278 | 25.278 | 25.278 | 0 | 0 | 0 | 6587 | 26 | IA0046 | 84 | 55 | 2 |
| 14 | 17 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.81 | 6587 | 16 | IA0046 | 84 | 55 | 2 |
| 15 | 17 | 1 | 0.627 | 0.127 | 19.792 | 0 | 0 | 26.028 | 26.028 | 12.145 | 6273 | 14 | IA0046 | 84 | 55 | 2 |
| 16 | 17 | 3 | 0.026 | 0.026 | 1.531 | 1.531 | 1.531 | 0 | 0 | 0 | 5870 | 5 | IA0046 | 84 | 55 | 2 |
| 17 | 11 | 1 | 0.627 | 0.127 | 19.792 | 0 | 0 | 26.028 | 26.028 | 12.145 | 6273 | 27 | IA0048 | 83B | 74 | 1.82 |
| 18 | 11 | 1 | 0.279 | 0.084 | 8.796 | 0 | 0 | 11.568 | 11.568 | 5.398 | 6273 | 14 | IA0048 | 83B | 74 | 1.82 |
| 19 | 10 | 1 | 0.098 | 0.05 | 3.079 | 0 | 0 | 4.049 | 4.049 | 1.889 | 6273 | 14 | IA0048 | 83B | 74 | 3.5 |
| 20 | 11 | 1 | 0.418 | 0.103 | 13.194 | 0 | 0 | 17.352 | 17.352 | 8.096 | 6273 | 14 | IA0048 | 83B | 74 | 1.82 |
| 21 | 10 | 1 | 0.558 | 0.119 | 17.593 | 0 | 0 | 23.136 | 23.136 | 10.795 | 6273 | 14 | IA0048 | 83B | 74 | 3.5 |
| 22 | 10 | 3 | 0 | 0 | 18.539 | 18.539 | 18.539 | 0 | 0 | 0 | 6119 | 28 | IA0048 | 83B | 74 | 3.5 |
| 23 | 8 | 1 | 0.098 | 0.05 | 3.079 | 0 | 0 | 4.049 | 4.049 | 1.889 | 6273 | 14 | IA0046 | 84 | 55 | 1.92 |
| 24 | 16 | 4 | 0.651 | 0.129 | 18.925 | 18.925 | 18.925 | 0 | 0 | 0 | 6587 | 20 | IA0048 | 83B | 74 | 2.02 |
| 25 | 16 | 4 | 0.465 | 0.109 | 13.518 | 13.518 | 13.518 | 0 | 0 | 0 | 6587 | 20 | IA0048 | 83B | 74 | 2.02 |

| Farm ID | SWAT sub-basin | Farm type | Openlot (ha) | Grass buffer (ha) | CCCCCC (ha) | CSCSCS (ha) | SCSCSC (ha) | CCOAA (ha) | AAOCC (ha) | Pasture (ha) | Manure appl. rate (kg/ha) | Fert file # | S5 ID | Soil map unit ID | Slope length (m) | Slope (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 15 | 1 | 0.418 | 0.103 | 13.194 | 0 | 0 | 17.352 | 17.352 | 8.096 | 6273 | 14 | IA0063 | 177 | 61 | 1.62 |
| 27 | 13 | 2 | 0 | 0 | 60.729 | 0 | 0 | 0 | 0 | 20.243 | 6587 | 16 | MN0121 | 213B | 53 | 2.12 |
| 28 | 10 | 2 | 0 | 0 | 7.287 | 0 | 0 | 0 | 0 | 2.429 | 6587 | 16 | IA0048 | 83B | 74 | 3.5 |
| 29 | 10 | 2 | 0 | 0 | 18.219 | 0 | 0 | 0 | 0 | 6.073 | 6587 | 16 | IA0048 | 83B | 74 | 3.5 |
| 31 | 12 | 3 | 0 | 0 | 5.088 | 5.088 | 5.088 | 0 | 0 | 0 | 6119 | 10 | IA0048 | 83B | 53 | 7.92 |
| 32 | 28 | 4 | 0.465 | 0.109 | 13.518 | 13.518 | 13.518 | 0 | 0 | 0 | 6587 | 20 | IA0046 | 84 | 55 | 3.5 |
| 33 | 28 | 1 | 0.488 | 0.112 | 15.394 | 0 | 0 | 20.244 | 20.244 | 9.446 | 6273 | 14 | IA0046 | 84 | 55 | 3.5 |
| 34 | 28 | 1 | 0.836 | 0.146 | 26.389 | 0 | 0 | 34.704 | 34.704 | 16.193 | 6273 | 14 | IA0046 | 84 | 55 | 3.5 |
| 35 | 24 | 3 | 0 | 0 | 32.227 | 32.227 | 32.227 | 0 | 0 | 0 | 6119 | 10 | IA0040 | 198B | 75 | 1.62 |
| 36 | 31 | 1 | 0.349 | 0.094 | 10.995 | 0 | 0 | 14.46 | 14.46 | 6.747 | 6273 | 14 | IA0048 | 83B | 75 | 2.92 |
| 37 | 31 | 1 | 0.983 | 0.159 | 31.007 | 0 | 0 | 40.777 | 40.777 | 19.026 | 6273 | 29 | IA0048 | 83B | 75 | 2.92 |
| 38 | 22 | 1 | 0.418 | 0.103 | 13.194 | 0 | 0 | 17.352 | 17.352 | 8.096 | 6273 | 14 | MN0121 | 213B | 53 | 4.02 |
| 39 | 23 | 1 | 0.488 | 0.112 | 15.394 | 0 | 0 | 20.244 | 20.244 | 9.446 | 6273 | 14 | MN0104 | 151 | 53 | 11.22 |
| 40 | 23 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8.097 | 3764 | 17 | MN0104 | 151 | 53 | 11.22 |
| 41 | 28 | 1 | 0.349 | 0.094 | 10.995 | 0 | 0 | 14.46 | 14.46 | 6.747 | 6273 | 14 | IA0046 | 84 | 55 | 3.5 |
| 42 | 30 | 4 | 0.093 | 0.049 | 2.704 | 2.704 | 2.704 | 0 | 0 | 0 | 6587 | 20 | IA0048 | 83B | 74 | 3.5 |
| 43 | 31 | 1 | 0.279 | 0.084 | 8.796 | 0 | 0 | 11.568 | 11.568 | 5.398 | 6273 | 14 | IA0040 | 198B | 75 | 2.92 |
| 44 | 27 | 3 | 0.315 | 0.09 | 18.526 | 18.526 | 18.526 | 0 | 0 | 0 | 5870 | 30 | IA0113 | 499B | 61 | 9.5 |
| 45 | 29 | 1 | 0.488 | 0.112 | 15.394 | 0 | 0 | 20.244 | 20.244 | 9.446 | 6273 | 14 | IA0069 | 109B | 49 | 7 |
| 46 | 29 | 3 | 0 | 0 | 16.317 | 16.317 | 16.317 | 0 | 0 | 0 | 6119 | 31 | IA0069 | 109B | 49 | 7 |
| 47 | 29 | 4 | 0.186 | 0.069 | 5.407 | 5.407 | 5.407 | 0 | 0 | 0 | 6587 | 20 | IA0069 | 109B | 49 | 7 |
| 48 | 29 | 4 | 0.232 | 0.077 | 6.759 | 6.759 | 6.759 | 0 | 0 | 0 | 6587 | 20 | IA0069 | 109B | 49 | 7 |
| 49 | 35 | 1 | 0.244 | 0.079 | 7.697 | 0 | 0 | 10.122 | 10.122 | 4.723 | 6273 | 14 | MN0104 | 151 | 53 | 4.5 |
| 50 | 35 | 1 | 0.488 | 0.112 | 15.394 | 0 | 0 | 20.244 | 20.244 | 9.446 | 6273 | 14 | MN0104 | 151 | 53 | 4.5 |
| 51 | 35 | 1 | 0.418 | 0.103 | 13.194 | 0 | 0 | 17.352 | 17.352 | 8.096 | 6273 | 14 | MN0104 | 151 | 53 | 4.5 |
| 52 | 44 | 4 | 0.465 | 0.109 | 13.518 | 13.518 | 13.518 | 0 | 0 | 0 | 6587 | 20 | MN0104 | 151 | 53 | 2.92 |

| Farm ID | SWAT sub-basin | Farm type | Openlot (ha) | Grass buffer (ha) | CCCCCC (ha) | CSCSCS (ha) | SCSCSC (ha) | CCOAA (ha) | AAOCC (ha) | Pasture (ha) | Manure appl. rate (kg/ha) | Fert file # | S5 ID | Soil map unit ID | Slope length (m) | Slope (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 53 | 35 | 1 | 0.53 | 0.116 | 16.713 | 0 | 0 | 21.979 | 21.979 | 10.255 | 6273 | 32 | MN0104 | 151 | 53 | 4.5 |
| 54 | 32 | 1 | 0.488 | 0.112 | 15.394 | 0 | 0 | 20.244 | 20.244 | 9.446 | 6273 | 14 | IA0048 | 83B | 74 | 5.02 |
| 55 | 51 | 1 | 0.084 | 0.046 | 2.639 | 0 | 0 | 3.47 | 3.47 | 1.619 | 6273 | 14 | IA0087 | 407B | 84 | 16.22 |
| 56 | 43 | 2 | 0 | 0 | 36.437 | 0 | 0 | 0 | 0 | 12.146 | 6587 | 16 | MN0104 | 151 | 53 | 3.42 |
| 57 | 36 | 2 | 0 | 0 | 42.51 | 0 | 0 | 0 | 0 | 14.17 | 6587 | 16 | IA0062 | 171B | 66 | 2.92 |
| 58 | 42 | 2 | 0 | 0 | 24.291 | 0 | 0 | 0 | 0 | 8.097 | 6587 | 16 | IA0062 | 171B | 66 | 3.5 |
| 59 | 33 | 2 | 0 | 0 | 30.364 | 0 | 0 | 0 | 0 | 10.121 | 6587 | 16 | IA0062 | 171B | 66 | 2.82 |
| 62 | 30 | 1 | 0.042 | 0.033 | 1.319 | 0 | 0 | 1.735 | 1.735 | 0.81 | 6273 | 14 | IA0048 | 83B | 74 | 3.5 |
| 63 | 31 | 1 | 0.349 | 0.094 | 10.995 | 0 | 0 | 14.46 | 14.46 | 6.747 | 6273 | 14 | IA0040 | 198B | 75 | 2.92 |
| 64 | 34 | 3 | 0.13 | 0.058 | 7.655 | 7.655 | 7.655 | 0 | 0 | 0 | 5870 | 5 | IA0046 | 84 | 55 | 4.52 |
| 65 | 49 | 4 | 0.929 | 0.154 | 27.035 | 27.035 | 27.035 | 0 | 0 | 0 | 6587 | 20 | MN0104 | 151 | 53 | 13.12 |
| 66 | 47 | 4 | 0.265 | 0.082 | 7.705 | 7.705 | 7.705 | 0 | 0 | 0 | 6587 | 33 | IA0113 | 499B | 61 | 9.5 |
| 67 | 47 | 1 | 0.209 | 0.073 | 6.597 | 0 | 0 | 8.676 | 8.676 | 4.048 | 6273 | 14 | IA0113 | 499B | 61 | 9.5 |
| 68 | 51 | 1 | 0.349 | 0.094 | 10.995 | 0 | 0 | 14.46 | 14.46 | 6.747 | 6273 | 14 | IA0087 | 407B | 84 | 16.22 |
| 69 | 47 | 1 | 0.139 | 0.06 | 4.398 | 0 | 0 | 5.784 | 5.784 | 2.699 | 6273 | 14 | IA0113 | 499B | 61 | 9.5 |
| 70 | 47 | 1 | 0.139 | 0.06 | 4.398 | 0 | 0 | 5.784 | 5.784 | 2.699 | 6273 | 14 | IA0113 | 499B | 61 | 9.5 |
| 71 | 44 | 3 | 0 | 0 | 45.796 | 45.796 | 45.796 | 0 | 0 | 0 | 6119 | 10 | MN0104 | 151 | 53 | 2.92 |
| 72 | 52 | 3 | 0.104 | 0.052 | 6.124 | 6.124 | 6.124 | 0 | 0 | 0 | 5870 | 5 | IA0082 | 40 | 34 | 13.92 |
| 73 | 49 | 3 | 0.013 | 0.018 | 0.766 | 0.766 | 0.766 | 0 | 0 | 0 | 5870 | 5 | MN0104 | 151 | 53 | 13.12 |
| 74 | 47 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10.121 | 3764 | 17 | IA0113 | 499B | 61 | 9.5 |
| 75 | 44 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8.097 | 3764 | 17 | MN0104 | 151 | 53 | 2.92 |
| 76 | 35 | 1 | 0.174 | 0.067 | 5.498 | 0 | 0 | 7.23 | 7.23 | 3.373 | 6273 | 14 | MN0104 | 151 | 53 | 4.5 |
| 77 | 40 | 1 | 0.112 | 0.053 | 3.519 | 0 | 0 | 4.627 | 4.627 | 2.159 | 6273 | 14 | MN0104 | 151 | 53 | 4 |
| 78 | 40 | 1 | 0.174 | 0.067 | 5.498 | 0 | 0 | 7.23 | 7.23 | 3.373 | 6273 | 14 | MN0104 | 151 | 53 | 4 |
| 79 | 40 | 1 | 0.105 | 0.052 | 3.299 | 0 | 0 | 4.338 | 4.338 | 2.024 | 6273 | 14 | MN0104 | 151 | 53 | 4 |
| 80 | 40 | 1 | 0.836 | 0.146 | 26.389 | 0 | 0 | 34.704 | 34.704 | 16.193 | 6273 | 14 | MN0104 | 151 | 53 | 4 |

| Farm ID | SWAT sub-basin | Farm type | Openlot (ha) | Grass buffer (ha) | CCCCCC (ha) | CSCSCS (ha) | SCSCSC (ha) | CCAAA (ha) | AAACC (ha) | Pasture (ha) | Manure appl. rate (kg/ha) | Fert file # | S5 ID | Soil map unit ID | Slope length (m) | Slope (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 81 | 41 | 3 | 0 | 0 | 66.149 | 66.149 | 66.149 | 0 | 0 | 0 | 6119 | 10 | IA0048 | 83B | 74 | 3.5 |
| 82 | 41 | 4 | 0.302 | 0.088 | 8.787 | 8.787 | 8.787 | 0 | 0 | 0 | 6587 | 20 | IA0048 | 83B | 74 | 3.5 |
| 83 | 41 | 1 | 0.941 | 0.155 | 29.688 | 0 | 0 | 39.042 | 39.042 | 18.217 | 6273 | 14 | IA0048 | 83B | 74 | 3.5 |
| 84 | 46 | 3 | 0 | 0 | 91.591 | 91.591 | 91.591 | 0 | 0 | 0 | 6119 | 10 | MN0104 | 151 | 53 | 3.5 |
| 85 | 45 | 1 | 0.418 | 0.103 | 13.194 | 0 | 0 | 17.352 | 17.352 | 8.096 | 6273 | 14 | MN0104 | 151 | 53 | 13.22 |
| 86 | 44 | 1 | 0.237 | 0.078 | 7.477 | 0 | 0 | 9.833 | 9.833 | 4.588 | 6273 | 14 | MN0104 | 151 | 53 | 2.92 |
| 87 | 40 | 3 | 0.208 | 0.073 | 12.249 | 12.249 | 12.249 | 0 | 0 | 0 | 5870 | 5 | MN0104 | 151 | 53 | 4 |
| 88 | 46 | 3 | 0 | 0 | 22.898 | 22.898 | 22.898 | 0 | 0 | 0 | 6119 | 10 | MN0104 | 151 | 53 | 3.5 |
| 89 | 6 | 3 | 0 | 0 | 8.481 | 8.481 | 8.481 | 0 | 0 | 0 | 6119 | 10 | MN0104 | 151 | 55 | 1.92 |
| 90 | 6 | 2 | 0 | 0 | 65.587 | 0 | 0 | 0 | 0 | 21.862 | 6587 | 16 | MN0104 | 151 | 55 | 1.92 |

[a] The open lot and grass buffer were assumed to be pasture areas for SWAT HRU areas

[b] CC = Continuous corn, CS = corn-soybean, SC = Soybean-corn, CCCAAA = corn-corn-alfalfa-alfalfa-alfalfa, AAACC = alfalfa-alfalfa-alfalfa-corn-corn

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